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JOURNAL

OF

THE ROYAL SOCIETY

OF

WESTERN AUSTRALIA, INC.

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Vol. XXXVI

The Authors of Papers are alone responsible for the statements
and
the opinions expressed therein.

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JOURNAL OF THE ROYAL SOCIETY OF WESTERN AUSTRALIA.

VOLUME XXXVI.

1.—THE INTERNAL STRUCTURE OF SOME WESTERN AUSTRALIAN CRETACEOUS BRACHIOPODS.

By

GRAHAM F. ELLIOTT.

Communicated by Mr. P. J. Coleman, 9th August, 1949.

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I. INTRODUCTION.

The existence of Cretaceous strata in Western Australia has been known since the middle of last century, the best-known and most fossiliferous deposit being the Gingin Chalk, from which numerous organic remains have been described ; the best list of references is found in the general account of the formation by Glauert (1910, 1925). The discovery of the free crinoids *Uintacrinus* and *Marsupites* (Withers 1924, 1926), which mark a definite horizon in the European Upper Chalk (Senonian) and have a very wide distribution, the latter occurring in the Upper Cretaceous of all five continents and the former in three of them, fixes the age of the Australian formation as Santonian (Middle Senonian), a global correlation permissible with these non-sessile organisms.[1] More recently Clarke and Teichert (1948) have described the outcrop about 250 miles north of the Gingin district, of a similar chalky bed, the Toolonga Chalk, which yielded a very similar fauna including the zonal crinoids, and which appears to represent another portion of the same Senonian off-shore littoral. The writer, interested in the discovery in this second area of the brachiopods already described by Etheridge (1913) from the Gingin Chalk, and in the resemblance of the Murchison House Series (to which the Toolonga Chalk belongs) to the familiar Cretaceous succession in the South of England, communicated with Professor Clarke, who readily and generously entrusted a quantity of Senonian brachiopod material from Western Australia to him for study. It is mostly on this collection that the account given below is based. All three species studied, when dissected to reveal the internal structures, yielded results of considerable interest, and the palaeogeographic significance of the new generic determinations is discussed accordingly.

(1) See Sieverts (1927) for discussion on the locomotion of living free crinoids with special reference to *Marsupites* and mention of *Uintacrinus*.

II. DESCRIPTION OF THE SPECIES.

Family **TEREBRATULIDAE** Gray.

Genus **INOPINATARCULA** gen. nov.

(Reference is to the homoeomorphy with *Trigonosemus*)

Biconvex capillate terebratulids, with stout cardinalia, stout hinge-teeth with swollen bases, and wide loop.

Inopinatarcula acanthodes (Etheridge).

Plate II, figs. 22–27.

1913. *Trigonosemus acanthodes :* R. Etheridge fil. *Bull. Geol. Surv. W. Australia*, No. 55, p. 15, pl. 2, figs. 1–4.

Diagnosis.

Shell about 22 mm. long, 22 mm. wide, and 11 mm. thick ; biconvex, rounded-pentagonal, spinose-capillate, anterior commissure uniplicate. Test thick, very finely punctate. Umbo short, suberect, truncated ; foramen very small, circular, permesothyrid ; symphytium rugose, area concave, hinge-line subterebratulid ; stout hinge-teeth with grooved swollen bases, interior of beak greatly constricted, pedicle-valve muscle marks deep and heartshaped. Cardinalia strong ; inner and outer socket-ridges, crural bases and outer hinge-plates present ; cardinal process transverse ; loop, short, wide with arched transverse band ; brachial-valve muscle-marks both raised and depressed.

Hypotypes.

Thirty-two specimens in the collection of the Geol. Dept., University of Western Australia.

Description.

(a) External. This flattened terebratulid, which attains a length and breadth of 22 mm. in the series examined, is most commonly rounded pentagonal in outline, with sides formed by the shoulder-slopes, curved lateral commissures and anterior commissure ; a minority of individuals show a terebratulid hinge-line instead of the normal subterebratulid one, so that the maximum width occurs anterior of the normal position at half the shell-length, with consequent alteration in the outline. In young shells (length 7 mm.), the anterior curve runs in a half circle from the shoulder slopes, the pentagonal outline being eventually attained at about 14 mm. shell-length. The commissure is markedly uniplicate in the adult ; this feature is feebly developed in the 7 mm. examples and accentuates during subsequent growth to a wide rounded curve in the adult, occasioned by a broad median plica in the brachial valve opposed by a similar sulcus in the pedicle valve. In occasional examples this fold rises so steeply that the shell becomes selliform. Both valves are densely capillate from umbo to margin, new capillae arising both by intercalation and bifurcation, and very occasionally reuniting : at the margin of an adult specimen about four such rounded capillae with three flattened interstices occupy 1 mm. Sporadic lines of interruption of growth, sometimes step-like, cross the capillae which are irregularly set with small scattered spinose projections. These spines are only visible on well-preserved specimens, and are most densely set around the umbones, on the earlier formed portion of the shell ; as growth proceeds they appear more sparsely, though there is considerable variation in this respect. The test is very finely punctate, the punctae being only visible with a magnification of about x20.

The pedicle-valve palintrope is concave, and is bounded by the cardinal margin and by the two beak-ridges meeting at the pin-hole foramen just below the apex. The symphytium is in the form of a low equilateral triangle and shows well-marked transverse growth-lines, and is bounded by narrow ill-defined interareas ; outside these, to left and right, the remainder of the palintrope shows the continuation of pedicle-valve growth-lines across the rounded beak-ridges. The height of the palintrope is about one eleventh of the shell-length in the adult.

(b) Internal : pedicle valve. The interior of this valve is smooth, rising along the anterior-posterior mid-line as the internal expression of the external median sulcus which commences inconspicuously and widens to the anterior commissure. Posteriorly the anterior of the umbo and region of the hinge-teeth are very heavily calcified, the symphytium being fused to and covering a solid umbo perforated only by a thread-like tunnel leading down from the pin-hole foramen ; this tunnel emerges as a narrow notch sloping steeply down to the posterior point of the muscle-area described below. Left and right of the notch the walls of the calcified foundations of the hinge-teeth curve anteriorly and outwards and diverge. The hinge-teeth, large and massive, lie to left and right anterior of the corners of the symphytium, and are deeply notched half-way between the floor of the valve and the tops of the teeth. These notches widen posteriorly to spoon-like depressions, and the socket-ridges of the brachial valve interlock in them. Externally the teeth are delimited from the edges of the valve by narrow grooves.

The muscle-marks form a heart-shaped area, widening anteriorly from the calcified umbonal structures and terminating at about a third of the shell-length. They are deeply marked and visible as a translucent area on the opaque shell. This area is divisible into separate muscle-scars. At the foot of the pedicle-notch a raised tongue—or teat-shaped deposit of callus points anteriorly ; immediately anterior of this is an elongate median paired scar.

Two large fimbriate scars occupy the anterior portion of the whole area, and there are two poorly defined lateral scars. These last occupy the position of the main pedicle-muscles in some living brachiopods : the large scars apparently represent the diductors, the median paired scar the adductors, though it is small for this purpose, and the tongue-shaped callus possibly the attachment of the subsidiary pedicle-muscle. Successive growth-attachments of the supposed adductors within the median scar show as concentric lines.

All these details of the pedicle-valve are best seen on adult specimens in which the median fold is only moderately developed.

(c) Internal : Brachial valve. The interior of the valve is smooth, marked by a median antero-posterior depression of variable development, the opposite feature to the median fold seen within the pedicle-valve, and usually less prominent owing to the brachial valve being flatter. The cardinalia are well-developed, and various separate structures are distinguishable. The sockets are wide and triangular, the callus which floors them forming slight rounded outer socket-ridges immediately within the valve-margins ; on the inside, the sockets are overhung by high massive inner socket-ridges which are externally visible in a posterior view of the valve like the hinge-projections in *Terebratulina*, overhanging the outer socket-ridges near the umbo. On the inner side of the inner socket-ridges, the slopes are obliquely downward and concave to two sharp edges, divergent from the umbo : these

edges are undercut by the steep wall-like descent of the solid divided cardinalia, either side, to the floor of the valve, the loop being attached to the walls. The concave surfaces are interpreted as outer hinge-plates, though not shelf-like anteriorly as is typical for this structure, and the inner edges as crural bases, from the loop-attachment. The transverse cardinal process is situated just inside the umbo and shows a posterior concave roughened surface and a smooth anterior bulbous surface above the descent to the valve-floor, the two surfaces separated by a denticulate edge. The loop is wide and short ; from the crural bases the upper edges of the ribbons curve inwards to form the curve, the ribbons themselves diverging anteriorly at about 26° from the midline to about one third of the length of the valve and then curving upwards and backwards to form a transverse band so broadly curved that the two side-slopes are much closer to the descending branches than to each other.

All these structures are naturally best seen on mature specimens, but it should be noted that the immature loop in a brachial valve of 7 mm. length is proportionally much narrower than the adult loop.

The muscle-marks of the adult valve show two deep and conspicuous pyriform scars whose rounded anterior terminations are a little short of the half-way position along the valve-length. These scars are each sub-divided by a transverse ridge. Between them is a raised platform of callus extending forwards from the sharp descent within the umbo. The pyriform scars are interpreted as adductors ; the pedicle-muscles could have been attached either to the median callus or to the hinge-plates.

Remarks.

Inopinatarcula is a distinctive terebratuloid which does not suggest close affinity to any form known to the writer. The loop is somewhat similar in general appearance to that of *Aguehasia* as figured by Davidson (1886, pl. 7, fig. 3), but this little genus differs very much in size, characters of the beak, etc. The Australian shell is easily distinguished from the European *Trigonosemus*, to which it was first referred, by the coarse costate ornament and much higher area of the latter, which has a very different internal structure with massive cardinal process, strong median septum and long loop. The classification of the Terebratulidae or short-looped forms is at present unsatisfactory, but there can be no doubt of the distinctness of the present form nor of its claim to generic rank.

Family **DALLINIDAE** Allan, 1940.

Subfamily **KINGENINAE** Elliott, 1948.

Genus **KINGENA** Davidson, 1852.

Kingena mesembrina (Etheridge).

Plate I., figs. 1–13.

1913 *Magas mesembrinus* ; R. Etheridge fil., *Bull. Geol. Surv. W. Aust.*, No. 55, p. 15, pl. 2, figs. 5–8.

Diagnosis.

Shell about 18 mm. long, 16 mm. wide and 9 mm. thick, biconvex rounded pentagonal to elongate-oval, test thin, externally finely granulose and conspicuously punctate, anterior commissure feebly sulcate. Umbo short, suberect, truncated ; foramen moderately large, circular, permesothyrid ; deltidial plates disjunct and obscured by the beak-ridges, hinge-line terabratulid.

Hinge-teeth supported by dental lamellae, joined by sessile pedicle-collar. Cardinalia showing strong fused inner socket-ridges and crural bases, wide hinge-trough and transverse cardinal process ; kingeniform loop supported by a short median septum. Muscle-marks and pallial sinuses faint.

Hypotypes.

Twenty-one specimens in the collection of the Geological Department, University of Western Australia : eight specimens in the collection of the Perth Museum.

Description.

(a) External. This shell varies somewhat in outline, though easily recognisable. Specimens which are rounded pentagonal in outline include the largest individuals. This type is thin-shelled, the fossils often being crushed ; and the commissure, if sulcate, is very feebly so, showing some tendency to ligate opposite folding ; there are no marked lines of interruption of growth. The other type is slightly thicker-shelled, elongate-oval in outline, and shows slight but definite sulcation. The test for the species as a whole shows on well-preserved shells the fine external surface granules characteristic of the genus ; the punctation is coarse but regular and close-set. Some shells show faded orange-brown or reddish colouration : this was recorded by Davidson (1852, p. 45) for English *K. lima ;* and the living *Laqueus* and *Frenulina,* with loops similar to *Kingena,* are often attractively coloured. The greatest thickness of the pedicle-valve occurs at half the shell-length, but the corresponding dimension of the brachial valve occurs at about one-third of the valve-length anterior of the umbo. The internal median septum is externally visible as a dark streak for two-fifths of the length of the brachial valve. At the umbo, short and suberect, the foramen, moderately large and circular, is seen to be permesothyrid in position; the beak-ridges, strong at the umbo, fade out quickly to left and right. In most specimens these beak-ridges are close to and obscure the area above the dorsal umbo, but in young examples two disjunct triangular deltidial plates are seen, and one such example showed these bordered by narrow interareas, with the remainder of the palintrope showing transverse growthlines to left and right below the beak-ridges.

(b) Internal—Pedicle-valve. The hinge-teeth lie at the outer corners of the delthyrium, and are supported by clearly-visible dental lamellae, nearly vertical, the bases on the valve-floor being slightly closer than the upper limits immediately under the teeth, and leaving clear cavities anteriorly between the lamellae and the sides of the valve ; posteriorly (towards the umbo) the lamellae are somewhat convergent. On the floor and sides of the beak-interior is a thickish sessile pedicle-collar, covering or passing into the dental lamellae up to the deltidial plates. Anteriorly the termination of the collar is clearly-marked, forming a posteriorly curved step between the two lamellae, so that its median length is shorter than at the sides. It shows concentric growth-lines parallel to the anterior margin.

The muscle-marks are obscure, forming an oval patch immediately anterior of the pedicle-collar. Faint but more prominent are four anteriorly radiating lines, an inner pair left and right of the muscle-marks, and then an outer pair ; these are traces of the main pallial sinuses.

(c) Internal—Brachial valve. In this valve the cardinalia are simple but distinctive. To left and right the valve floor rises to the rounded edges of the curved anterior margins of the socket floors, which separate from the valve-floor inwardly, so that the cardinalia are undercut. At the same time these anterior socket-margins curve upwards, are joined by the crural bridges of the loop, and thicken to overhang the sockets and to extend posteriorly as prominent inner socket-ridges meeting the valve margin left and right of the umbo ; there are no distinct outer socket-ridges. Immediately within the umbo the cardinal process shows as a transverse, very low-equilaterally triangular concave surface, but without any swollen surface below its anterior edge. A stout rather low median septum joins the cardinalia anteriorly and spreads into a conspicuous wide concave hinge-trough which lies between the cardinal process and the inner slopes of the inner socket-ridges proper. The floor of the hinge-trough is anteriorly free of the valve-floor in continuation of the socket-floors and is supported by the median septum. This is the normal pattern of cardinalia seen in young and adult shells. In the largest example examined, however (length of brachial valve 18 mm., shell-length 21 mm.), well-defined hinge-plates are seen on the insides of the socket-ridges, the septum running in at a lower level some distance before passing into a steep slope up to the cardinal process. Presumably the pedicle-muscles were normally attached to the inner slopes of the socket-ridges, and with increasing curvature of the umbonal portion of the valve during growth in this old specimen the slopes become converted to shelves or true hinge-plates, the hinge-trough proper becoming merely the posterior slope described above. The phenomenon is of some interest since normally the details of the cardinalia, unlike those of the loop, individualise during growth without definite appearance of new structures. Unless such old individuals are commoner than the collection studied suggests, hinge-plates should not be considered characteristic of the species.

The loop is typically kingeniform (Ref. Davidson, 1852, p. 41). From the cardinalia the crura extend anteriorly, giving rise to crural processes of moderate length curving inwards : the descending branches run forwards, outwards and downwards, and on their inner sides widely-attached connecting bands narrow inwards and connect them to the septum. The descending branches then curve upwards and inwards in a wide sweep, running back as ascending branches to turn inwards and meet in a very wide high transverse band, almost vertical to the floor of the valve. This transverse band continues downward as two inward and backwardly (anteriorly) curved connections to the median septum, joining it above the connecting bands from the descending branches and within the curve sketched by the crural processes, and so leaving a narrow gap in the box-like loop when viewed posteriorly. Laterally the loop resembles a butterfly with raised folded wings ; anteriorly two pairs of connections to the septum are clearly visible one above the other within the recurved loop-bands. The descending branches are fringed externally with short spines, and anteriorly near the points of recurvature these spines become long and graceful, especially in young examples.

In adult examples the transverse band shows two angled folds above the vertical connecting bands. Large examples are usually found crushed when dissected.

No unbroken pre-Kingeniform immature loops were dissected ; the preparations obtained suggest an earlier dallinid growth-stage with septal

pillar, campagiform hood and descending branches with very wide attachment to the septum and long anterior spurs. The relation of the Kingeniform loop to other dallinid loop-patterns is fully discussed below.

The median septum from the hinge-trough rises to its highest at the points of loop-attachment—the type-figure (Etheridge, 1913, pl. II., fig. 8) shows a broken example without loop—and then rapidly descends to the valve-floor and fades out.

Two indistinct muscle-marks are seen on the valve-floor, left and right of the median septum.

Remarks.

The observed variations in size and shape of *Kingena mesembrina* fall within the extreme limits of variation of the European *K. lima*, a long-range species (Albian-Senonian) probably capable of subdivision ; but the characteristic external surface granules are smaller and more closely-set in the Australian species. The oval, thicker-shelled, markedly sulcate forms with numerous lines of interruption of growth, from which Etheridge's type-specimen was selected, are noteworthy, probably representing slightly stunted or slow-growing individuals. *Kingenas* as a rule show slight uniplicate folding, but it is not invariable ; sulcate individuals of *K. lima* occur in the British Cenomanian, and *K. granulifera* Stoliczka is figured as sulcate.

The Australian assemblage as a whole represents a distinct geographical species.

K. mesembrina shows the characteristic loop on which Davidson based the genus. The writer, discussing the loop-development of the Dallinidae (1948b, p. 311) pointed out that just as *Laqueus* and *Pictothyris* diverge from normal dallinid development by retention of the frenuliniform connecting bands between ascending and descending branches, so *Kingena* appears to represent a genus parallel to the terebrataliform which had retained its campagiform attachment to the septum, and so was referred to the new subfamily Kingeninae, with the expectation that the loop-development, when known, would confirm this. It is regretted that the present material did not permit observation of the full developmental series, though the broken campagiform loop, and the earliest complete loop, the latter somewhat reminiscent of that seen in a young adult *Frenulina*, are as expected. Meanwhile observations on other genera permit a slightly better understanding of *Kingena*. In the frenuliniform growth-stages both of the North Atlantic Recent *Waldheimiathyris cranium* and the British Cretaceous *Gemmarcula aurea* the posterior connecting bands individualised by the frenuliform lacunae join the median septum above the broad junction of the descending branches. In *Frenulina sanguinolenta* itself, in a small example which has just attained an adult loop, the ground-plans of the posterior connecting bands run obliquely out from the median septum, where they meet, across the attachments of the descending branches ; in a larger example the posterior connecting bands are set apart. Finally, in *Laqueus suffusus* the corresponding bands run from the ascending branches to the outside ends (left and right) of the attachments of the descending branches to the septum, but join the latter on the insides of the descending branches. It is not merely changes in the pattern of loop-structure, but proportional and orientational changes during growth, which bring about the final complicated forms of terebratelloid loops, as emphasised by the writer when considering

joint loop-and-lophophore development (*op. cit.*, p. 302). Now in *Kingena*, the progressive separation of the posterior connecting bands seen in the *Frenulina-Laqueus* series has not occurred, the original close attachment of posterior connecting bands separated by the posterior resorbed opening in the hood being retained with proportionally small increase in size, *pari passu* with the development of a very broad transverse band. Thus the frenuliniform lacunae eventually give rise, not to the spaces between ascending and descending branches more or less in one plane of *Laqueus*, but to the gaps with twisted boundaries formed by the descending branches, the connecting bands from these to the septum, the connections from the transverse band to the septum, and the ascending branches, as seen in the adult *K. mesembrina*.

The numerous spines on the loop of *Kingena* are reminiscent of those seen in various Jurassic zeillerid genera, and are met with in varying degree in dallinid genera, surviving in the young of the living *W. cranium*, but they do not occur in terebratellid genera. They are a further indication of the more primitive calcification of Dallinidae as compared with Terebratellidae.

Kingena mesembrina attained its kingeniform loop early: if the length of the shell at which an adult pattern of loop is attained[2] is expressed as a decimal of the length of the fully adult shell[3] the observed result is 0.32, perhaps a little less. This ratio is of interest, since there is good evidence in support of the view that terebratelloid loop-development has been brought about by intra-specific competition for food-supply in crowded brachiopod colonies, with resultant selection pressure in favour of a more efficient lophophore and its earlier attainment, and consequent modification of the supporting loop (Elliott, 1948a, b). Corresponding figures for *Mühlfeldtia truncata* (Linn.), *Terebratella dorsata* (Gmelin), *T. inconspicua* (Sowerby), *Magellania venosa* (Solander), *Neothyris lenticularis* (Desh.), *Waldheimiathyris cranium* (Muller), and *Dallina septigera* (Lovèn), all Recent, are 0.33–0.5; for the Recent *Dallinella obsoleta* (Beecher) 0.17.[4] *Kingena mesembrina* (Etheridge) and *Gemmarcula aurea* Elliott, both Cretaceous, give figures of 0.32 as stated, and 0.5 respectively. All these genera are in loop-pattern at the end or nearly so of their developmental series. For the Recent *Frenulina sanguinolenta* (Gmelin) and the Jurassic *Hamptonina buckmani* (Moore), lower genera in their developmental series, the figure is about 0.8.

Ignoring *Frenulina* and the Mesozoic genera for the moment, the remainder are temperate or cold-water forms, some being found in the cooler waters at considerable depths in lower latitudes. The increase in size of marine organisms in colder waters is a well-known phenomenon[5]; thus Sverdrup, Johnson and Fleming (1942, p. 857) say "Lowered temperatures lengthen the time required for poikilothermic animals to reach sexual maturity. Hence, in cold-water forms the delay permits a longer growing period with resultant larger size at maturity. It has been shown that the oxygen consumption of certain non-locomotory warm-water benthic species is higher than that of related cold-water species with which they were experimentally compared,

(2) This feature is subject to variation (cf. Fischer & Oehlert, 1892, p. 294 and expl. pl. XI.) on shell-size and loop-pattern attained in *Terebratella dorsata*, and the writer on a similar phenomenon with exterior structures in *Gemmarcula aurea* (Elliott, 1947, p. 147) but an average may be obtained for most species.

(3) Shell-length is a simple linear expression, adopted for convenience, of the cubic content of the shell to which the animal and its nourishment are related.

(4) These figures are obtained from published results or single series of specimens: the writer has not had sufficient material for a detailed study of this phenomenon

(5) For a brachiopod example cf. Wesenberg-Lund (1941 b) on shell-size in *Dallina septigera* (Loven) in the N. Atlantic.

and this difference in metabolism may have a bearing on the question." It is considered here that in the brachiopods under discussion this increase in size and length of life accompanied the progressively more rapid brachiopod lophophore-development with its corresponding effect on the loop, and that the operation of the two factors *par passu*, physical-physiological and biological-genetic, is shown by the small shell-size at which these terebratelloids attain a loop of adult pattern, relative to the maximum shell-size eventually attained. *Kingena* and *Gemmarcula* occur in almost non-coralliferous deposits and may be taken as temperate and listed with the others. *Frenulina*, however, is a warm-water coral-reef species in the Pacific, and the Jurassic *Hamptonina* occurs in a coralliferous deposit[6] ; both are small species[7]. It therefore seems possible that the early sexual maturity and more abundant food-supply of those shallow warm-water species which have managed to retain their position in face of molluscan competition (cf. Elliott, 1948c) leads to small size and slower loop-evolution. Further information, particularly on genera with primitive loops is desirable ; so little detailed information is available on brachiopod ecology that the unravelling of their evolutionary story, as apart from description of faunas, can scarcely be said to have begun.

Family **TEREBRATELLIDAE** King, 1850.
Subfamily **BOUCHARDIINAE** Allan, 1940.
Genus **BOUCHARDIELLA** Doello-Jurado, 1922.

Bouchardiella cretacea (Etheridge).
Plate II., figs. 14–21.

1913, *Magasella cretacea* : R. Etheridge fil., *Bull. Geol. Surv. W. Aust.*, No. 55, p. 16, pl. 2, figs. 9 12.

1915, *Magadina cretacea* : Etheridge : Thomson, *Trans. N.Z. Inst.*, xlvii., p. 399.

Diagnosis.

Shell about 5 mm. long, 4 mm. wide and 2 mm. thick ; biconvex (dorsal umbo flattened), elongate ovoid-pentagonal ; test smooth, thick, densely punctate, commissure sulcate ; beak short and nearly straight, beak-ridges sharp, foramen epithyrid to permesothyrid, symphytium fused with concave palintrope, hinge-line slightly sloping. Interior of pedicle-valve beak constricted, hinge-teeth stout with grooved swollen bases, muscle-marks anterior, well-marked, separated by median ridge. Brachial sockets deep, cardinal platform solid, socket-ridges prominent, muscle-pit posterior and subquadrate, septum high anteriorly, loop retrograde pre-magadiniform.

Hypotypes.

Sixty-two specimens in the collection of the Geological Department, University of Western Australia.

Description.

(a) External. This little shell, fully adult when it attains the dimensions given above, is smooth-surfaced without marked lines of interruption of growth, though with a magnification of x 12 the growth-lines are seen to be

(6) The doubtfully mature loops figured by Zittel (1870) are from reef deposits.

(7) The Recent species *Kingena alcocki* Joubin, related to *Frenulina*, occurs in deeper water ; and is larger, with a loop trending towards that of *Laqueus*.

irregular in prominence. The anterior commissure is markedly sulcate, the pedicle-valve curving to a blunt rounded carina whose slopes fall to the lateral commissures, and the brachial valve to a median sulcus within the normal curvature and anterior of the flattened umbonal region. In outline the shell is elongate-oval or obscurely pentagonal, the greatest width being a little anterior of the mid-point of the shell length ; earlier stages were perhaps proportionately a little wider, and certainly less sulcate. The test is thick and densely punctate. The symphytium, slightly concave, low and wide, appears blended with the rest of the pedicle-valve palintrope, and the whole, showing obscure transverse growth-lines, is bounded anteriorly by the two halves of the sloping hinge-line and posteriorly by sharp beak-ridges. The pedicle-valve beak is short and nearly straight ; the foramen, almost at right angles to the plane of the symphytium, normally occupies the termination of the beak and encroaches on the thickness of the beak-ridges at the apex, but sometimes cuts through to notch the symphytium-apex.

(b) Internal—Pedicle-valve. The interior of the beak of this valve is constricted by shell-thickening, though this is in no wise comparable in extent to the same phenomenon in *Inopinatarcula.* The hinge-teeth are stout and the bases merge below into the floor of the valve, constricting the interior of the beak posteriorly and diverging to merge anteriorly into the sides of the valve ; half-way up these bases are prominently notched for the reception of the brachial-valve socket-ridges. The hollow of the floor of the interior of the beak gives place suddenly at about one-third of the shell-length to a broad rounded and obscurely double median ridge extending to near the anterior commissure. Left and right of this ridge are two reniform muscle-marks with rounded anterior terminations at approximately three-fifths of the shell-length.

(c) Internal—Brachial-valve. The posterior third of this valve is occupied by a solid cardinal platform. Left and right are wide sockets, without outer socket-ridges : between them is the high cardinal platform proper, trapezoid in plan and narrowing posteriorly to terminate above the valve-umbo ; and with rounded outer edges to left and right overhanging the sockets and so corresponding to the inner socket-ridges of more conventional cardinalia. The posterior surface of the cardinal platform shows a shallow, rounded to heart-shaped muscle-pit with several concentric growthlines : the indentation is anterior. The larger anterior portion of the cardinal platform shows two subsidiary antero-posterior ridges lying between the socket-ridges. Anteriorly the cardinal platform falls steeply and is joined at the base by a broad low median septum. On each side of this is a small cave within the vertical face of the hinge-platform, left and right, and there is a third depression, less deep, above the septum.

The septum narrows anteriorly, curves upwards steeply to a high summit with limited anterior extension, then falls vertically to merge at the base in the median ridge corresponding to the external sulcus. From the upper part of the steep posteriorly-facing slope just below the summit, two curved lamellae extend, one each to left and right, narrowing and recurving to point to one another ; they vary somewhat in size and curvature in different specimens, and in old individuals become broad curved triangular plates with wide bases on the septum.

Two ill-defined elongate muscle-marks are seen on the valve-floor to left and right of the septum.

Remarks.

This species was compared by Etheridge to the Recent *Magadina cumingi*, then known as *Magasella* and referred by him to the same genus. On the dismemberment of *Magasella* Thomson (1915a, p. 399) referred the fossil to his genus *Magadina* (type-species *M. browni*) as one of several previously-described Australian forms which combined bouchardiform shape with magaselliform loops. The term magaselliform was stated by the same writer (1915b, p. 405) to cover both magadiniform and magelliform loop-patterns. As described above, however, the loop of *B. cretacea* is degraded pre-magadiniform, agreeing with that of *Bouchardia*. The muscle-marks and hinge-platform with anterior caves are also similar to those of *Bouchardia*, but the prominent inverted-V cardinal process of this genus is missing, and indicated only by the anterior indentation of the cardinalian muscle-pit, an early stage in the shift of the diductors from a concave to a convex attachment. This feature is as described for the S. American Cretaceous *Bouchardiella* (Doello-Jurado 1922, p. 200), which is stated to differ only from the Tertiary and Recent *Bouchardia* in the less-advanced cardinal process. If *Magadina browni* (Thomson), *Bouchardia rosea* (Mawe) and *Bouchardiella cretacea* (Etheridge) are compared side by side, the resemblances between all three are obvious, but the Cretaceous fossil is seen to incline towards *Bouchardia* rather than *Magadina*, resembling most closely the young of *B. rosea*. In *Bouchardia* the symphytium is blended with the rest of the palintrope and the foramen is epithyrid : in *Magadina* the symphytium is distinct and foramen permesothyrid. *B. cretacea* shows no distinct symphytium, and in the majority of species the foramen lies between the beak-ridges at the apex (epithyrid), though it may encroach on their thickness : only occasionally does it notch them and so become permesothyrid. *B. cretacea* is smaller and more elongate than the S. American type-series *Bouchardiella patagonica* (von Ihering), but this is only a difference of at most specific rank. The writer regrets that he has not been able to examine figures or specimens of the interior of *B. patagonica*, but the agreement of this feature in the Australian fossil with Doello-Jurado's description of it in the S. American one is so close that the former is here removed from *Magadina* to *Bouchardiella*, bearing in mind that it appears to be a form very close to the ancestral stock for both Magadinae and Bouchardiinae, as might be expected from its geological age[8]. As it possesses a degraded loop like that of the Bouchardiinae it seems unnecessary to erect a new genus for its reception.

Bouchardiella cretacea is thus another example of a terebratellid genus with a very primitive loop. The writer has elsewhere discussed the special ecological conditions considered as the indirect cause of loop-development. It must be pointed out, however, that although the sporadic progress of loop-evolution, due to the repeated confluence of selection-pressure and growth-rate mutation, might be supposed to average out the numbers of genera in each stage of development or bring them all to the final stages, this is not the case. Thus *Bouchardiella* is one of numerous primitive terebratellids with pre-magadiniform and magadiniform loops, modified as described above by reason of their permanence. No such variety exists in the primitive dallinids where the more primitive calcareous hood (as compared with the terebratellid ring) are rapidly modified, and only *Campages*[9] survives with a modified hood. The intermediate magelliform or frenuliniform stages are rare in either

(8) Cf. Thomson . . . " it is probable that *Bouchardia* is a retrograde genus from a forerunner of *Magadina*. " (1915a, p. 402), and " it is probable that in loop characters *B. rosea* is degenerate from stock originally possessing pre-Magadiniform characters " (1915b, p. 406).

(9) The writer has not been able to examine a specimen of *Jolonica*.

series, since the former passes imperceptibly into the terebratelliform, and in the latter the frenuliniform bands are easily resorbed or diverge during growth to give a terebrataliform or laqueiniform stage. Finally, the numerous terebratelliform and terebrataliform species indicate that these stages, like the premagadiniform and magadiniform, are more permanent and that further resorption is not essential. This is confirmed by the fact that during the development of *Dallina septigera* the terebrataliform stages persist through an increase in shell-length equal to the previous growth of the shell up to that stage (Fischer Oehlert, 1891) ; a similar state of affairs is indicated with the terebratelliform stage in *Neothyris lenticularis* as figured by Davidson (1886, pl. IX, figs. 10–13). Thus even when evolutionary progression is continuous it is likely to be irregular.

III. PALAEOGEOGRAPHIC SIGNIFICANCE OF THE FAUNA.

It remains to consider the significance of the presence of these three forms in the Senonian of W. Australia. The supposed occurrences of *Magas* and *Trigonosemus*, terebratellid genera found in the Upper Senonian of Europe, accompanied by *Magadina cretacea*, an early representative of a typically Tertiary Australian family has been taken as evidence supporting the origin of the Terebratellidae in the northern hemisphere, and migration to the Australasian region via the Tethys. Since the European and Australasian beds in question are of much the same age, the Terebratellidae might on these grounds have originated anywhere along the Tethys, migrating in both directions ; however, *Magas* and *Trigonosemus*, as shown above, are erroneous determinations for the Australian species. Moreover, there is other European evidence to be be considered. *Magas* and *Trigonosemus*, referred to the Terebratellidae by reason of their loop and cardinalia respectively, appear suddenly in the Senonian of W. & N. Europe[10], accompanied in Scandinavia by *Rhynchora* and *Rhynchorina* which are stated to have *Magas*-like loops by Eudes-Deslongchamps (1884) and Oehlert (1887) respectively[11] and presumably spreading during the period of reduced selection-pressure consequent on the extensive and continued marine transgression in this region[12]. Previous to this, there are doubtful records of *Magas pumilus* from Cenomanian and Turonian (Jukes-Brown 1904), various species referred on external form alone to *Magas* and *Trigonosemus* (e.g. *M. geinitzi* Schloenbach and T. *incertus* Davidson from the Cenomanian), and the genus *Terebrirostra* similarly referred to the terebratellidae on account of its cardinalia and ranging from Neocomian to Cenomanian. An investigation of the internal structure of these and other doubtful forms, and if possible of their loop-development, is necessary to settle this question ; meanwhile the balance of such evidence as is available does support a European origin for the Terebratellidae.

Dealing now with the three Australian forms in the light of the new evidence, *Inopinatarcula* is a new form and whilst adding to the variety of described forms possesses no palaeogeographic significance as yet.

Bouchardiella cretacea is a southern form. The distribution of the brachiopods from the Recent and Tertiary of the Southern hemisphere was exhaustively discussed by Thomson (1918, p. 58), who concluded that " The dis-

(10) *Trigonosemus* sp. occurs in the Senonian (probably Maestrichtian) of N. Turkey. Record by courtesy of the Directors and Chief Geologist, Messrs. Iraq Petroleum Co., Ltd., London.

(11) Cf. also *Morrisia ? suessi* Bosquet and *Terebratella decorata* and *T. Lujani* Vidal, from the Maestrichtian of Belgium and Spain respectively.

(12) For an illustration of the reverse phenomenon in this region during early Tertiary times ref. Elliott (1948c).

tribution of Southern Recent brachiopods . . . is satisfactorily explained by an ancestral distribution in the Miocene . . . The generic similarities between the four southern Oligocene-Miocene faunas[13], on the other hand, are of such a nature as to demand at some earlier date much greater means of intercommunication between the lands bordering the South Pacific Ocean than exist at the present day. So far as the genera are concerned they might have occurred as far back as the Cretaceous . . ."

As explained above, *B. cretacea* agrees with the Patagonian *B. patagonica* in structure and geological age and they are Upper Cretaceous representatives of a considerable fauna, mostly Tertiary. The reference of the Australian fossil to *Bouchardiella* here is a matter of convenience, and it appears to be a form very near the ancestral junction of Bouchardinae and Magasinae. Whether such forms had spread from Europe to escape extinction and give rise to the higher Terebratellidae in Southern seas must remain unknown, but it is at least possible. *Tanakura* and *Nipponithyris*, from the Miocene and Recent respectively of Japan, presumably indicate a Tertiary northward Pacific migration, much as *Waldheimiathyris* (*Macandrevia auct.*) has migrated Southwards through the post-Miocene Pacific to the Antarctic (Thomson 1927, p. 241), but the doubtful little terebratelloid described by the writer from the French Eocene (Elliott 1940) may possibly be a European post-Cretaceous survivor. Whether the S. American and Australian species represent two forms of many along the Gondwanaland coast, surviving to our notice by reason of the present non-submergence of the rocks in which they occur, or whether some degree of continental drift accounts for their present wide separation, is beyond the scope of this paper. The writer, in W. Europe, has found little need to invoke the agency of continental drift, but better acquaintance with the problems of the Southern hemisphere, where the widely-separated land-masses show close stratigraphic and faunal resemblances, even with animal parasites (ref. Eichler, 1949), might change his views.

Kingena mesembrina offers evidence of a different kind, and extends the geographical distribution of this genus to all five continents. Species have been referred to *Kingena* from Jurassic, Cretaceous, Eocene and Recent. Of these, the Jurassic forms are probably not *Kingena*, *e.g.*, the Lebanon fauna described by Krumbeck (1905)[14], and *K. raincourti* E.-Desl. and *K. constantinensis* Cossm. and Pisarro, very rare in the French Eocene, are possibly post-Cretaceous survivors, possibly new forms. Investigation of the internal structure is necessary to confirm the final reference of all these fossils to a genus. The recent *K. alcocki* Joubin has been shown to be a related form to *Frenulina* and *Laqueus* (Jackson 1921 ; Thomson 1927, pp. 242 43). In the Cretaceous, the variable *K. lima* (Defr.), the type-species, ranges from Albian to Senonian in Europe, and neither Davidson (1852, pp. 43–44) or Eudes-Deslongchamps (1887) could decide on its separation into stratigraphical species, though this is no doubt possible with the aid of statistical population-studies, as with certain large foraminifera ; *e.g.*, Henson (1948) on *Orbitolina*. Other Cretaceous forms recognisable as *Kingena* by the external form, surface ornament where preserved and beak characters are *K. wacoensis* (Roemer)[15] common in the Texan Cretaceous, N. African records of *K. lima* (Peron 1893, Daque 1903), *K. umbaghghikensis* Shalem from the Dead Sea area in

(13) Australia, New Zealand, S. America, Antarctica.
(14) See also Muir-Wood (1935) on *Zeillera latifrons* (Krumbeck).
(15) Loop figured by Cooper, in Shimer & Schrock (1944).

S.W. Asia, and the Indian species described by Muir-Wood (1930) from the N.W. and Stoliczka (1872) from the S. To these may be added the present Australian species.

If the geographic location of the above is considered it is seen that they all occur closely to the Tethys, being distributed by the world-wide marine transgressions of the upper half of the Cretaceous, from the Albian onwards. Of the Australian brachiopods considered, then, *Kingena* is the link with other areas : its occurrence in Australia fitting in with a probable lower Cretaceous origin and upper Cretaceous dispersal. It does not add to the zonal information furnished by *Marsupites* and *Uintacrinus* but the world-wide dispersal of a brachiopod belonging to a type with very limited larval opportunities for dispersal does indicate exceptional opportunities for migration, for whilst such slow migration is rapid in comparison with sedimentation, there are usually land and deep-sea barriers to prevent wide brachiopod dispersal (cf. Thomson 1927, p. 47). Such opportunities, in the present state of our knowledge, are best indicated by the Cretaceous Tethys and its transgressions.

IV. FURTHER NOTES ON TEREBRATELLOID EVOLUTION[16].

Since the writing of this account some additional evidence has come to hand. The statement of Thomson (1927, p. 289) is quoted in support of the strictly local development of loop-progression " *Neothyris* is merely a *Pachymagas* which has attained the magellaniform loop stage," and he points out that in New Zealand species of the former suddenly replace those of the latter, with but one exception, at one Oligocene horizon, and only *Neothyris* survives in the Pliocene : whilst in Patagonia *Pachymagas* survived till the Pliocene and apparently did not give rise to *Neothyris*.

This local development was considered to be due to the crowded terebratelloid brachiopod communities, consequent upon limited opportunities for larval migration (cf. Blochmann, 1908, on the Norwegian species). Additional evidence on this point may now be given from the Scandinavian region. Detailed studies of the plankton of the fjords (*e.g.*, Runnström, 1932) have confirmed the absence of the larvae of the bottom-living brachiopods in the higher layers of water. In the elaborate and detailed study of the planktonic larvae of bottom-living animals in the Danish Öresund by Thorsson and collaborators (1946) no trace of brachiopod larvae was found, although a substantial proportion of the larvae are swept in by the bottom current from the Kattegat and even from the more distant Skagerrak to the North, and at least one brachiopod species is known to occur as far south as the former (Wesenberg-Lund, 1941a). This latter writer refutes the one record of an adult brachiopod from the Sound as a probable error (*op. cit.*, p. 4). It seems clear, therefore, that only very limited opportunities for terebratelloid larval dispersal exist normally when compared with some other invertebrates. Whether the ability to delay metamorphosis pending discovery of a suitable ground anchorage, as in certain polychaetes (Day & Wilson, 1934 : Wilson, 1937, 1948) exists in brachiopods is unknown, but the evidence amassed suggests that, if present, it is at best feebly developed. Similarly the deeper-water brachiopod larvae must be completely photonegative and not change during growth in this respect as described for some other invertebrates with

(16) Ref. Elliott (1948b).

a surface-layer phase by Thorsson (*op. cit.*, pp. 462–63), though photosensitivity is only a secondary evolutionary adaption as compared with the duration of the larval stage.

It remains to consider the implications of terebratelloid evolution with regard to taxonomy. The history of the classification of terebratuloids and terebratelloids was reviewed by Thomson (1927, pp. 165–179). Briefly, the early concept of a terebratelloid genus as comprising those forms with a common pattern of loop was displaced when it was realised that such aggregates were polyphyletic and that the different stocks were indicated by the more slowly-evolving cardinalia. Subsequent practice has been to define a genus as comprising those forms within a cardinalian stock which have a common adult pattern of loop, the family and subfamily groupings being based on loop-development. This is convenient practice, although the writer has pointed out that it is possible for one species in such a genus to arise repeatedly from the parent stem at different times ; two species in one genus may undergo parallel development into two comparable species in another genus[17]. Both these cases are at variance with the common unwritten concept of a genus as a group of related forms different in detail as a result of geographical or ecological migration, but expression of the difference taxonomically would make the nomenclature burdensome. It has been suggested that an investigation of the chromosomes and hybridisation—possibilities of brachiopods in one line of loop-progression would be of interest (Elliott, 1948, p. 312) : certainly from the present point of view it would clearly indicate the degree of biological and hence of taxonomic importance to be attached to the pattern of adult loops. Meanwhile the existing practice outlined above is as good as any.

V. SUMMARY.

The species *Trigonosemus acanthodes*, *Magas mesembrinus* and *Magasella cretacea*, described by Etheridge (1913) from the Gingin Chalk, are now redescribed in detail and referred by reason of their internal structure to the genera *Inopinatarcula* nov., *Kingena* Davidson and *Bouchardiella* Doello-Jurado respectively. The palaeogeographic significance of *Kingena* with regard to the Tethys, and of the occurrence of *Bouchardiella* both in Australia and S. America, is discussed : also the evolutionary significance of the stage at which an adult loop is attained in the former genus, and of the type of loop in the second genus. Finally, some fresh evidence bearing on brachiopod migration, and the implications of terebratelloid evolution on taxonomy, are reviewed.

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(17) The average of specific characters—shape, outline, adult size and colouration—changes from one species to another, genetically when new colonies are derived from a few individuals and also as a result of selection for the new environment. Thus subsidiary stocks based on specific characters, within cardinalian stocks, are not as a rule distinguishable though colour-patterning may persist (cf. Thomson, 1927, p. 291).

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KEY TO SYMBOLS ON PLATES I AND II.

a = ascending branch
asc = adductor muscle-scar
bl = bouchardiform lamella
br = beak-ridge
c = crus
cb = crural base
cp = cardinal process
d = descending branch
dbc = connection from descending branch to septum
dl = dental lamella
dp = deltidial plate
f = foramen
dsc = diductor muscle-scar
g = groove of hinge-tooth
h = hinge-trough
hpl = hinge-platform
i = interarea
ihp = inner hinge-plate
isr = inner socket-ridge
iss = slope of inner socket-ridge
ka = posterior aperture of loop
lc = lateral beak cavity
lcv = lateral cave
mcl = median callus
mf = median fold
mm = muscle-mark
mr = median ridge
ms = median septum
mv = median cavity
mx = matrix
ohp = outer hinge-plate
osr = outer socket-ridge
pat = posterior attachment of loop
pc = pedicle-collar
ps = pallial sinus-mark
psc = pedicle muscle-scar
pt = pedicle tunnel
s = hinge-socket
sp = spine
sy = symphytium
tb = transverse band
tbc = connection from transverse band to septum
te = hinge-tooth
tr = muscle-trough

Explanation of Plates.

PLATE I.

Figs. 1-13. *Kingena mesembrina* (Etheridge). All from the Chalk (Senonian) of the Gingin District, Western Australia.

1. Brachial valve with loop from an individual of 8.25mm. shell-length, side view.
2. The same, posterior view.
3. The same, anterior view.
4. The same, seen from above.
5. Brachial valve with broken loop from an individual of 12mm. shell-length, lateral-oblique view.
6. Pedicle valve from an individual of 8.25mm. shell-length, anterior view.
7. Brachial valve, posterior half, with loop embedded in matrix; specimen of 21mm. shell-length.
8. Pedicle valve from a distorted individual of about 9mm. shell-length.
9. Brachial valve, posterior view of same specimen as in Fig. 7.
10. Brachial valve view of posterior portion of specimen of 10mm. shell-length.
11. Adult shell, side view.
12. Small variety, anterior view.
13. The same, brachial valve view.

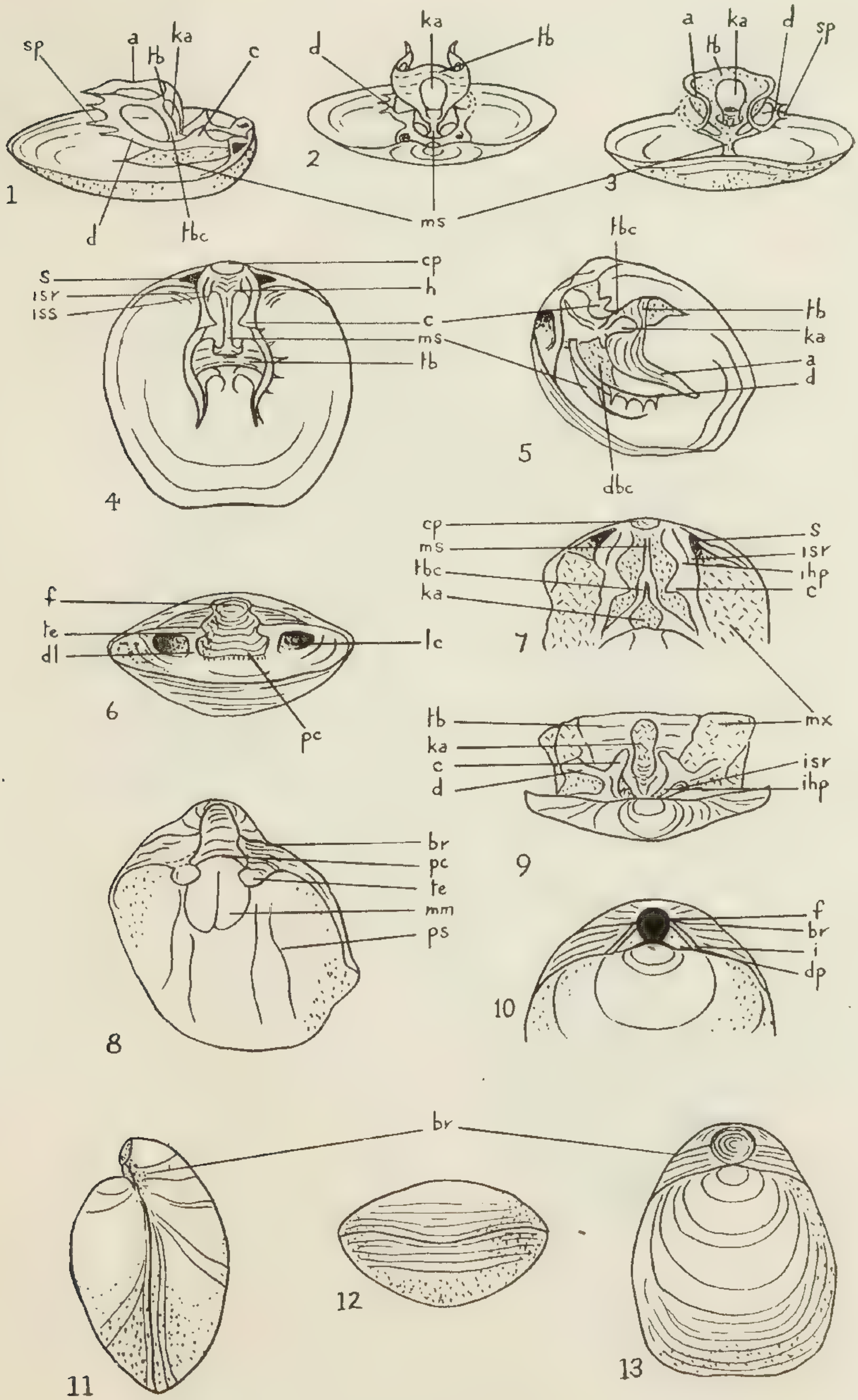

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Plate I.

PLATE II.

Figs. 14-21. *Bouchardiella cretacea* (Etheridge). All from the Chalk (Senonian) of the Gingin District of Western Australia.

14. Brachial valve with broken loop.
15. Individual with pedicle valve mostly broken away, showing old loop, side view.
16. Individual with pedicle valve mostly broken away, showing earlier loop, side view.
17. Pedicle valve.
18. Brachial valve view of bivalved individual.
19. Same specimen as in Fig. 15, interior.
20. Same specimen as in Fig. 16, interior.
21. Same specimen as in Fig. 18, anterior view.

Figs. 22-27. *Inopinatarcula acanthodes* (Etheridge). Nos. 22, 24, 26, from the Chalk of the Gingin District; Nos. 23, 25, 27, from the Toolonga Chalk of the lower Murchison River Area: Senonian, Western Australia.

22. Adult brachial loop and cardinalia.
23. Broken pedicle valve, interior.
24. Immature brachial valve with loop, from specimen of 9mm. shell-length.
25. Individual of 16.5m. shell-length, brachial valve view.
26. Interior of brachial valve with broken loop, to show muscle-scars.
27. Diagrammatic anterior view of same specimen as in Fig. 25.

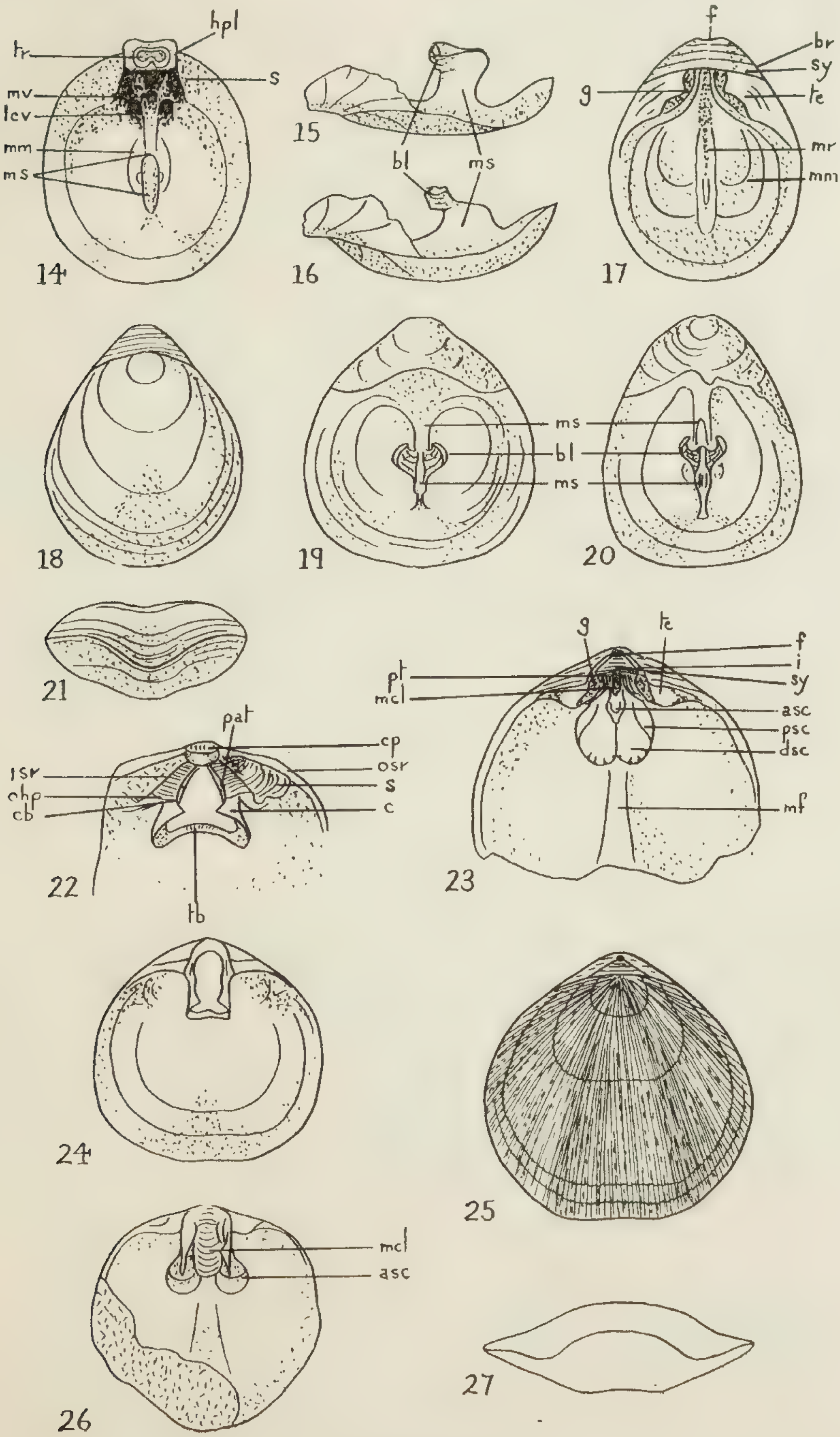
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Plate II.

2.—WESTERN AUSTRALIAN OPILIONES.

By

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Communicated by Mr. L. Glauert, 14th March, 1950.

The following paper is based on the collection of opilionids in the Western Australian Museum. I wish to thank Mr. L. Glauert, Curator, Western Australian Museum for his kindness in permitting this material to be forwarded to New Zealand for examination. The collection comprises a large series of Laniatores and a few Palpatores. Unfortunately all the Palpatores are immature and thus cannot be dealt with. However it is of interest to record that the claws of the pedipalps of all the specimens are strongly pectinate and therefore would fall in the sub-family Megalopsalinae (Forster 1949), not as was previously thought, in the sub-family Phalangiinae. The collection of Laniatores includes three species, *Bindoona glauerti* Roewer (family Phalangodidae), *Nunciella aspera* (Pocock) and *Dingupa glauerti* n.gen.n.sp. (family Triaenonychidae). In the present paper *Dingupa glauerti* n.gen.n.sp. is described and *Nunciella aspera* (Pocock) redescribed, while *N. frontalis* Roewer is listed as a synonym of *N. aspera.*

Family **TRIAENONYCHIDAE** Sorensen.

Sub-Family **ADAEINAE** Pocock.

Genus **DINGUPA** nov.

Eyemound only slightly removed from the anterior margin of the cephalothoracic carapace and armed with a small apical spine. Scutum lacking spines. Areas 1–5 clearly defined by transverse grooves. Areas 1–4 each divided into a number of plates by longitudinal grooves. Sternum narrowly triangular. Chelicerae small and lacking spines. Pedipalps relatively well developed and strongly spined. Tarsal formula 3, 5, 4, 4. Distitarsi of leg 1, two-segmented, leg 2, three-segmented. Side branches of tarsal claws of legs 3 and 4 smaller than median prong. Calcaneus small. Spiracles hidden. Sexual dimorphism present in the chelicerae and the spines of the anterior margin of the cephalothoracic carapace.

Genotype **Dingupa glauerti** n.sp.

This genus may be immediately distinguished from all described Australian Triaenonychids by the structure of the scutal areas. I have a number of species of an as yet undescribed New Zealand genus which is also characterised by a similar structure of the scutum. I have placed *Dingupa* in the sub-family Adaeinae which is characterised by a broad sternum. However I do not believe that the separation of sub-families on the shape of the sternum reflects any phylogenetic trend in this family and that the Triaenonychidae should be completely revised.

Dingupa glauerti n.sp.

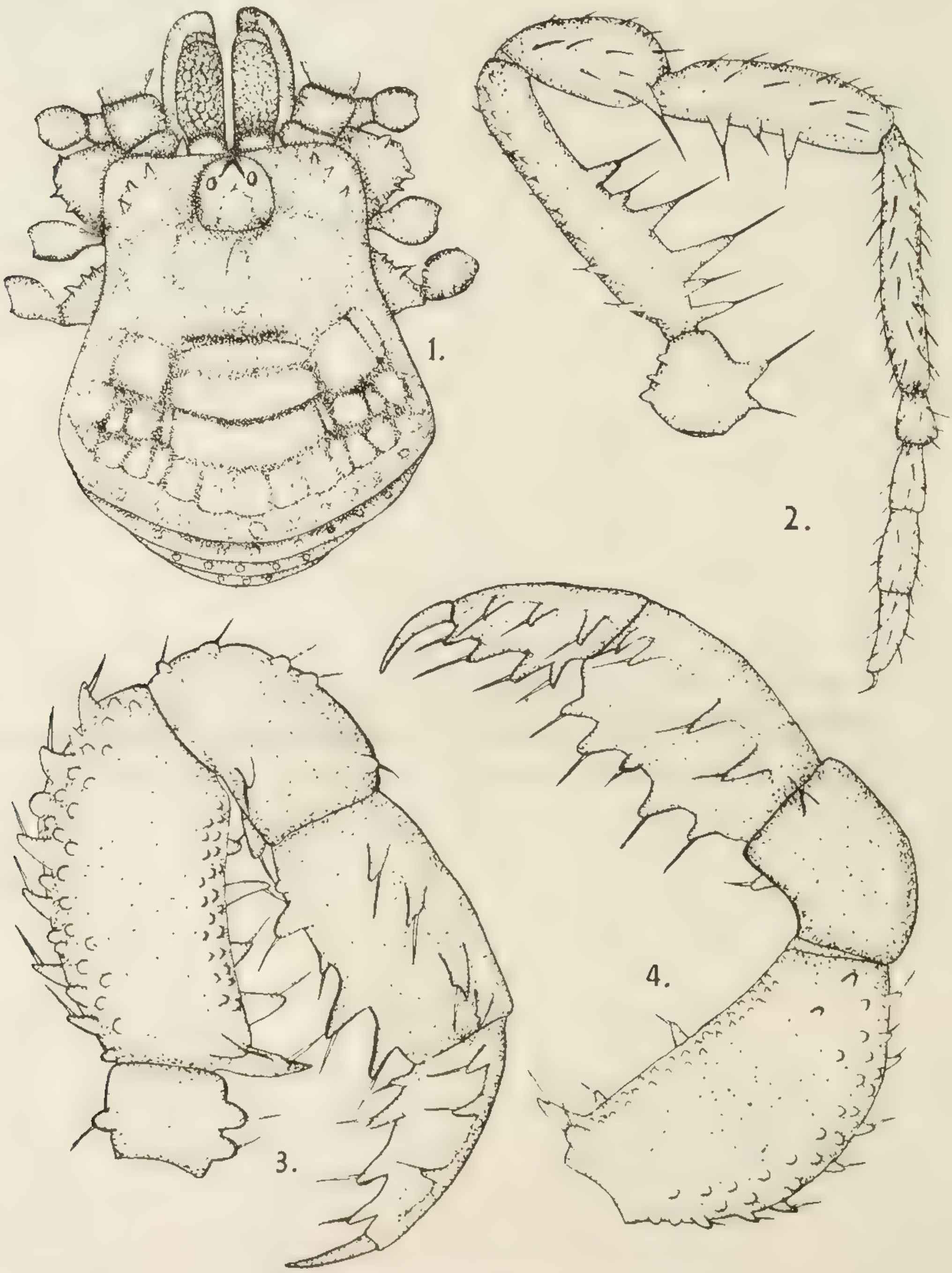
Text figs. 1–5.

MALE.

Measurements. Length of body .... 2·24
Width of body .... 1·68

	Cox.	Troch.	Fem.	Pat.	Tib.	Met.	Tars.	Total.
Leg 1	0·48	0·24	0·74	0·39	0·58	0·74	0·49	3·66
Leg 2	0·54	0·24	0·93	0·48	0·94	1·04	0·68	4·85
Leg 3	0·58	0·29	0·93	0·38	0·69	0·79	0·54	4·20
Leg 4	0·61	0·34	1·14	0·44	1·04	1·13	0·69	5·39
Pedipalp	....	0·35	0·94	0·45	0·54	....	0·38	2·66
Chelicera....		Basal 0·64		Second 0·78				1·42

Colour.—Body dark brown but with a few orange-yellow markings on the cephalothoracic carapace (text fig. 1). The appendages are orange-yellow with irregular black markings.



Text figs. 1-4: *Dingupa glauerti* n.sp.
1, Dorsal view of body; 2, Leg 1; 3, Retrolateral view of pedipal; 4, Proventral view of pedipalp.

Body (text fig. 1).—The eyemound is as wide as high. It slopes steeply up from the anterior margin of the carapace but slopes gently back down the posterior surface. A short forwardly directed spine is situated anterior to the eyes. The anterior margin of the carapace is entire and unarmed except for two strong spines, one at the retrolateral margin of each chelicera. The surface of the carapace is rough in appearance but not granulate. A row of three small spines extend obliquely across each anterior corner of the carapace. The carapace is separated from the scutum by a deep transverse groove. The five scutal areas are clearly defined. A large median plate is present on each of areas 1–3. The median plates of areas 1 and 2 are bounded on each side by a large single plate. A series of four small irregularly shaped plates extend to the lateral margins each side of the median plate of area 3. Area 4 is broken up into a row of plates, square in the median region but irregularly shaped laterally. Area 5 is not divided into plates. A transverse row of four large granules is present on the median surface of areas 1–4. A transverse row of granules extends across area 5, of which the median one is largest. The three free tergites and all sternites have each a transverse row of small granules. The spiracles are hidden. The sternum is relatively broad and genital operculum is smooth and shaped as shown in text fig. 5.

Chelicerae.—These are small. The basal segment is smooth and constricted proximally where the dorsal surface forms a smoothly rounded knob. A line of small setose tubercles extends along the dorsal surface of the second segment, which is otherwise unarmed.

Pedipalps (text fig. 4).—These are relatively well developed. There is one small spine on the ventral and a further small spine on the dorsal surface of the trochanter. The ventral surface of the femur is armed with a large proximal spine followed by two smaller spines, one at one-fifth and the other at half-way. A large rounded tubercle is present prolateral to the proximal spine and the entire ventral surface is closely covered with small granules. The dorsal surface is covered with numerous small spines and there is also a line of eight larger spines extending along the mid-line. The patella is smooth except for two small spines, one on the ventral surface and the other on the distal surface. Four strong spines are present on the prolateral surface of the femur, of which the distal pair are adjacent. The retrolateral surface of the femur is armed with five spines, of which the third is small. The tarsus is armed with three spines on the prolateral surface and four on the retrolateral surface. The tarsal claw is strong.

Legs.—Numerous small tubercles are distributed on the coxae as shown in text fig. 5. Leg 1 is spined as follows (text fig. 2). Trochanter, two on ventral surface. Femur, six along proximal two-thirds of ventral surface. Patella, one on prodistal surface. Tibia, three along ventral surface. Metatarsus and tarsus smooth. The remaining legs are unarmed except for small setose tubercles. The calcaneus is much shorter than the astralagus. Tarsal formula 3, 5, 4, 4. Distitarsus of leg 1, two-segmented, leg 2, three-segmented. Side branches of legs 3 and 4 much shorter than median prong.

FEMALE.

Measurements. Length of body .... 2·13
Width of body .... 1·74

	Cox.	Troch.	Fem.	Pat.	Tib.	Met.	Tars.	Total.
Leg 1	0·34	0·19	0·62	0·33	0·48	0·53	0·39	2·88
Leg 2	0·54	0·13	0·88	0·39	0·63	0·68	0·87	4·12
Leg 3	0·54	0·12	0·74	0·29	0·54	0·53	0·44	3·20
Leg 4	0·69	0·13	0·94	0·39	0·84	1·05	0·54	4·58
Pedipalp	....	0·19	0·48	0·28	0·33	....	0·29	1·57
Chelicera	Basal 0·43		Second 0·54					0·97

The female is much smaller than the male, but as it is very similar to the male in structure differing only in the following features.

The basal segment of the chelicera is not constricted in the proximal region as in the male and the spines at the retrolateral margin of the chelicerae are small.

Although the pedipalps of the females are smaller than those of the males, the spines are relatively more strongly developed. There is a row of five spines along the ventral surface of the femur of which the third and fifth are small. The first spine on the retromargin of the tibia is reduced to a small tubercle. Otherwise the spination is similar (text fig. 3).

The spines of leg 1 are not as strong as in the male but otherwise the legs are similar. Tarsal formula 3, 5, 4, 4. Distitarsus of leg 1, two-segmented, leg 2, three-segmented.

Types.—Holotype male No. 36/2136, allotype female 36/2137, three paratype females 36/2136–36/2140, in collection of Western Australian Museum.

Locality.—All five specimens were collected by Mr. L. Glauert at Dingup in March, 1936.

Sub-family **TRIAENONYCHINAE** Pocock.

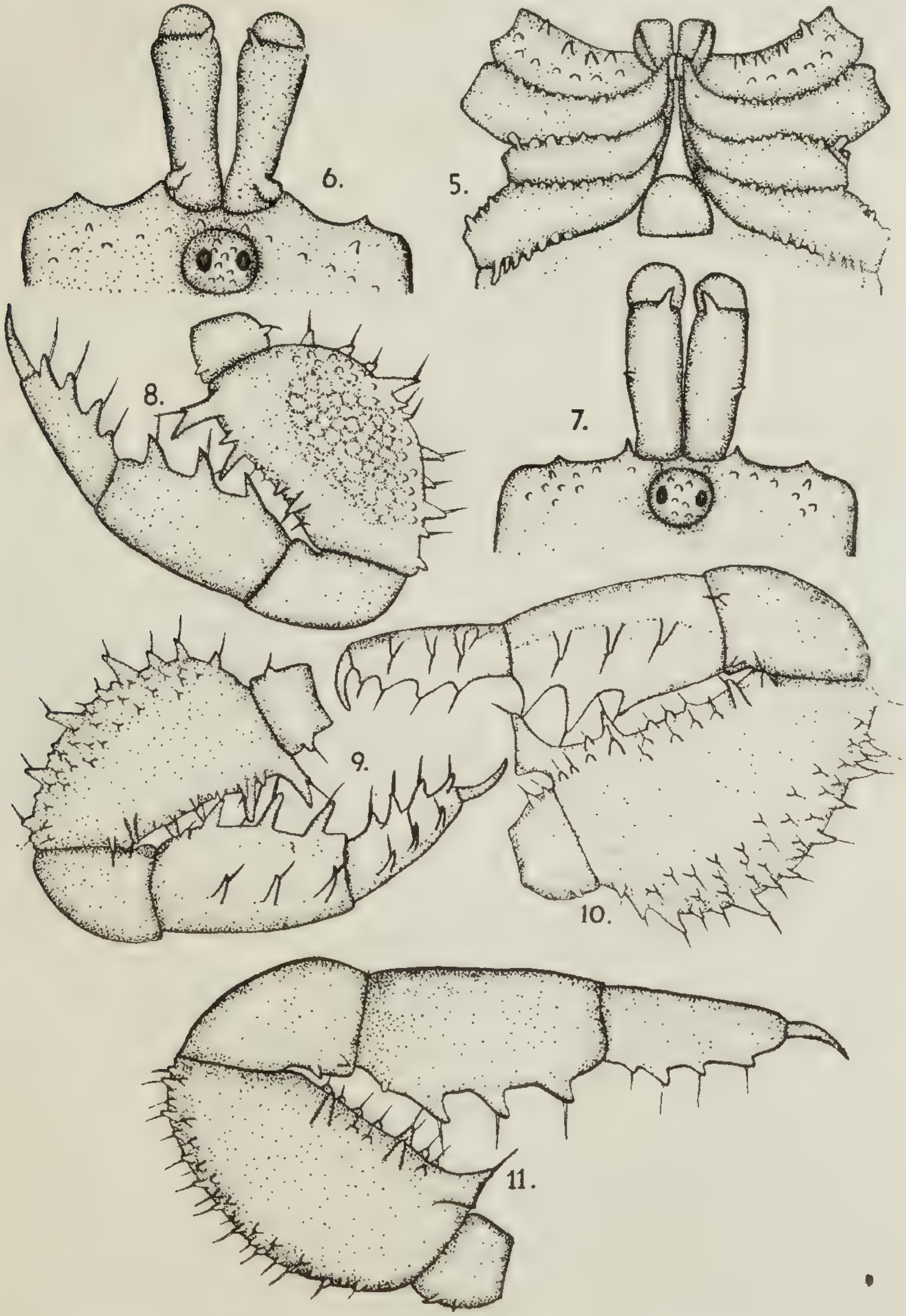
Genus **NUNCIELLA** Roewer 1929.

The genus *Nunciella* was established by Roewer (1929) for *Nuncia aspera* Pocock and separated from *Nuncia* Loman by the possession of four segments in the distitarsus of leg 2 as distinct from the three present in *Nuncia*. Roewer (1931) has since described four further species, *N. cheliplus*, and *N. parvula* from Victoria, *N. granulata* from New Zealand, and *N. frontalis* from Western Australia. In a recent paper (Forster, 1949) I have described a further species (*N. tuberculata*) from Victoria. During the examination of *N. tuberculata* a number of striking sexual differences were noticed. The ventro-proximal spine of the femur of the pedipalp is much expanded in the male and merely unevenly bifid in the female and the spine on the coxa of leg 1 against which this spine rests is correspondingly modified. Also a large rounded spine is present on the retro-proximal surface of the basal segment of the chelicera in the male but absent in the female. This sexual dimorphism is also present in the series of *N. aspera* under examination at present and was apparently overlooked by Roewer in 1929 when examining the same material. It seems probable that a similar dimorphism is found throughout this genus. If this is so it would appear that the figures of *N. frontalis* and *N. parvula* as given by Roewer (1931) are not of males as is stated in the caption but females.

Nunciella aspera (Pocock).

Text figs. 6–11.

1903 *Triaenonyx aspera* Pocock.
1910 *T. aspera* Loman.
1914 *Nuncia aspera* Roewer.
1923 *Nuncia aspera* Roewer.
1931 *Nunciella aspera* Roewer.
1931 *Nunciella frontalis* Roewer



Text fig. 5: *Dingupa glauerti* n.sp. Antero-ventral view of male.

Text figs. 6-11: *Nunciella aspera* (Pocock).

6, Antero-dorsal view of male; 7, Antero-dorsal view of female; 8, Retrolaterial view of female; 9, Prolateral view of female pedipalp; 10, Prolateral view of male pedipalp; 11, Retrolateral view of male pedipalp.

MALE.

Measurements.

Length of body .... 5·00
Width of body .... 3·74

	Cox.	Troch.	Fem.	Pat.	Tib.	Mte.	Tars.	Total.
Leg 1	1·08	0·44	1·79	0·74	1·28	1·67	1·00	8·00
Leg 2	1·29	0·54	1·83	0·68	2·14	2·53	2·48	11·49
Leg 3	1·18	0·49	1·88	0·69	1·34	1·54	0·94	8·06
Leg 4	1·74	0·84	2·35	0·73	1·89	1·64	1·13	10·32
Pedipalp....	....	0·48	1·98	1·09	1·27	....	1·04	5·86
Chelicera....	Basal 1·19		Second 1·54					2·73

Colour.—The ground colour of the body is ochreous-yellow overlaid with a regular black pattern on the dorsal surface. The chelicerae are light yellow. The pedipalps are ochreous yellow with black reticulate markings on the retrolateral surface of the femur. The legs are light yellow but are closely shaded with black.

Body (text fig. 6).—The eyemound from the anterior margin of the carapace by a distance equal to half of its width. It is almost as high as wide and rounded. From three to five irregularly placed granules are present on the dorsal surface. The anterior margin of the carapace is produced forward at the retrolateral margin of each chelicera to form a broad spine which rests against a large spine on the proximal surface of each chelicera. A further similar but smaller spine is present on the anterior margin of the carapace which rests on the retrolateral surface of the trochanter of leg 1. Behind each of these latter spines is situated a small erect spine. A row of small granules extend across the carapace anterior to the eyemound to the lateral margins. The entire cephalothoracic carapace and scutum are sparsely covered with small granules. A small transverse groove visible only on the median surface divides the cephalothoracic carapace from the scutum. The scutum lacks spines and is not divided by transverse grooves. A transverse row of small whitish spines is present along the posterior margin of the scutum and each free tergite. Each sternite has a single transverse row of small granules. The genital operculum is smooth, flat, and almost rounded in outline. The inner half of the maxillary lobe of coxa 2 is produced forward as a lobe, the anterior surface of which is broadly truncate.

Chelecirae.—These are small. The basal segment is slender proximally but is distended distally and armed with a large blunt spine on the retroproximal surface and a smaller sharp spine on the medio-distal surface (text fig. 6). The second segment is armed with a few small setose tubercles on the mediodorsal surface and a strong spine on the retro-distal surface.

Pedipalps (text figs. 10, 11).—These are robust. Three small spines are present on the patella, one mid-dorsal, one mid-ventral and the other retrodistal in position. The femur is armed with a line of five spines along the dorsal surface, the fourth and fifth being small. There are also numerous small setose tubercles present on the dorsal surface. The ventral surface is armed with a large obliquely truncated proximal spine followed by two large normal spines, while along the inner surface of these is a row of five small granules. Two further spines are present on the prolateral surface, one at four-fifths and the other distal. The patella lacks spines but a number of small scattered tubercles are present. The prolateral and the retrolateral surfaces of the tibia are each armed with three strong spines. The tarsus has four spines on the prolateral and three spines on the retrolateral surfaces. Tarsal claw strong.

Legs.—Three spines are present on coxa 1 of which the distal one is expanded distally where it is broadly truncate. All segments except the metatarsi and tarsi are covered with small setose tubercles. Tarsal formula 3, 12, 4, 4. The first segment of tarsus 1 is slightly larger than the remaining segments. Distitarsi of legs 1 and 2, two and four-segmented respectively. Side branches of claws of legs 3 and 4 much stronger than the median prong.

FEMALE.

Measurements.

Length of body .... 4·54

Width of body .... 3·21

	Cox.	Troch.	Fem.	Pat.	Tib.	Met.	Tars.	Total.
Leg 1	1·04	0·39	1·29	0·78	1·44	1·58	0·94	7·46
Leg 2	1·24	0·64	1·88	0·93	1·94	2·23	1·53	10·39
Leg 3	1·18	0·54	1·29	0·74	1·43	1·68	1·04	7·90
Leg 4	1·74	0·53	1·89	0·78	2·04	2·63	0·98	10·59
Pedipalp....	....	0·44	1·58	0·78	1·19	....	1·04	5·03
Chelicera....		Basal 0·94		Second 1·54				2·48

The female differs from the male in the following points :—

The large blunt spine found on the proximal surface of the basal segment of the chelicera of the female is lacking in the male. Corrolated with this the spine on the anterior margins of the carapace at the retrolateral margin of each chelicera is small. The pedipalps are not as large as those of the male (text figs. 8, 9). The dorsal surface of the femur is armed with a row of five strong spines and is covered with a few small setose tubercles. A large unevenly bifid spine is present on the proximo-ventral surface, followed by two strong simple spines. On the inner surface is a row of from 8–9 small setose tubercles. A pair of spines are present on the pro-distal surface. A pair of small spines are present on the disto-ventral surface of the patella. Three spines are present on the prolateral and retrolateral surfaces of both the tibia and tarsus.

Localities.—Pinjarra, Lunenberg, Brunswick, Bridgetown (Loman, 1910). Present collection, Darlington, Cape Leeuwin, Serpentine, Rottnest Island, Witchcliffe, Wellington Mills, Yallingup, Darlington, Calgardup. An extremely large series of eighty specimens were present in the collection from Calgardup, which Mr. L. Glauert informs me was only a small portion of a large assemblage found under a fallen log. (March 1940).

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3.—FORAMINIFERAL INVESTIGATIONS IN THE PERTH BASIN, WESTERN AUSTRALIA.

by

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Department of Geology, University of Western Australia.

Read: 11th April, 1950.

ABSTRACT.

Micro-faunal examination of five Perth artesian bores show the presence of Eocene and Cretaceous beneath a thin cover of Quaternary. In King's Park Bores 1 and 2, Recent-Pleistocene foraminifera occur down to 84 feet, Eocene forms from 84–780 feet, and probably Cretaceous varieties from 1,535–1,770 feet. In the Langley Park bore, Eocene foraminifera occur from 208–975 feet. An easterly dip is possible. The Belmont Park bore yielded few foraminifera but Eocene forms were found at 530 feet and sporadically between 840–900 feet. The Power House bore and the upper part of the Mt. Lyell (Bassendean) bore were unfossiliferous. Finer subdivision of the Eocene was inconclusive.

INTRODUCTION.

Comparatively little is known or published concerning the sedimentary layers which compose the coastal plain in the vicinity of Perth. The small angle of dip of these beds, their lenticular nature, the absence of outcrops, and the ubiquitous cover of recent sands and alluvium have made the discovery of their nature and structural relations extremely difficult. All that can be concluded, after allowing for the paucity of evidence, is that the beds beneath the Coastal Plain in the vicinity of Perth (the "Perth Basin"), are composed, to a depth of over 2,000 feet, of calcareous shales, mudstones, sandstones, and sands, overlain by Recent sands and in part, by Pleistocene limestones. Upper Eocene fossils have been found in some of these beds, generally at depths less than 800 feet. Below them, and at varying depths, between 1,550 feet to 1,800 feet, Cretaceous fossils have been found (Clarke, Prider and Teichert, 1944).

The structure of the beds beneath the Swan Coastal Plain must be intimately connected with the nature and history of the Darling Scarp. The generally accepted view as to the origin of the scarp is that it is a true fault scarp, post-Miocene in age (Saint-Smith, 1912, p. 70; Jutson, 1912, p. 149, and 1934, p. 86; Woolnough, 1918).

Recently it has been suggested (Prider, 1941, 1948) that the Darling Scarp is an erosion feature due to differential erosion of a monoclinal fold rather than a fault scarp, the observed characteristics of the scarp being explicable by the differential erosion of the hard Pre-Cambrian rocks to the east and the softer, later rocks to the west of the scarp. The down-warping he considers to have been in operation since late Pre-Cambrian times.

This suggests that the post-Proterozoic rocks of the Coastal Plain may descend to great depths, containing Mesozoic and older sediments beneath the already recognised Tertiaries. Deep drilling, using foraminiferal evidence and geophysical methods which would indicate the depth of the Pre-Cambrian bed rocks, is needed to test the truth of this hypothesis.

The Perth Basin has proved a useful artesian reservoir and the bore logs furnish what little is known of the stratigraphy and structure. This data is not altogether satisfactory because :—

(i) Comparatively few bores have been sunk, and few of these are deeper than 2,000 feet.

(ii) Very few of them have been sampled, and most of these were done rather haphazardly. Also many of the available samples are from percussion bores and are thus only mud samples, not actual cores.

(iii) The drillers' logs are rarely satisfactory from the geologists' point of view ; indeed, they are often more confusing than helpful.

(iv) Little work has been done on the fossil content of the bores.

(v) A large part of the area yields bore-samples which are completely unfossiliferous.

To date only two papers have been published concerning information yielded by bores. The first of these was an article by F. G. Forman (1933). This was the result of a comprehensive survey of most of the bores that had been put down in the metropolitan area prior to 1932, in an attempt at correlation based on the nature of the ground waters, dissolved salts, depths of the principal water horizons, static heads, temperatures of the waters, and to a certain extent, on lithology. The conclusion reached was that the information available was insufficient and of too doubtful a character to be used to produce accurate structural contour maps, but he succeeded in correlating the principal aquifers.

The second paper by Parr (1938) dealt with the description of the foraminifera found in samples from two adjacent bores—King's Park Nos. 1 and 2. He recorded nearly 70 species of foraminifera, some ostracoda, bryozoa, and sponge remains. He concluded that the age of the beds from which the samples came, between approximately 80 and 780 feet, were Upper Eocene.* The frequency chart compiled by Parr indicated that certain species could be used as index species and that particular assemblages characterised certain parts of the bore sections.

In an appendix to Parr's paper, it was noted that Lower Cretaceous foraminifera were also identified by Crespin from two other bores, the Leederville and Zoological Garden's bores, in samples from between 1,660 and 1,750 feet approximately.

Parr's results suggested that at least a rough zonal division of the upper beds was possible and prompted the examination by the writer of samples from five bores put down for artesian water. These samples had been stored in the Geology Department of the University of Western Australia for some years. The bores were percussion type, casing being used and kept within some 30 feet of the bottom. A certain amount of contamination was inevitable, but the range of contamination probably would not exceed 50 feet. They had been sampled with a fair degree of precision at approximately 20–30 feet intervals, and at noticeable changes in lithology. Many samples were scrapings from the bit as distinct from the less desirable bailer samples.

* Dr. R. W. Fairbridge informs the writer that he is proposing the name *King's Park Shale* for this sequence, while the underlying unfossiliferous formation is to be named the *Leederville Sandstone*. This in turn rests on the fossiliferous, Lower Cretaceous shales, for which he proposes the name *South Perth Shale*.

DESCRIPTION OF THE BORES.

The bores from which the samples came were :—

(i) The King's Park Bores, Nos. 1 and 2, put down near the Swan Brewery, Mount's Bay Road (see Locality Map, text fig. 1). Bore No. 1 at a depth of about 1,350 feet encountered a granite boulder and was abandoned. Bore No. 2, sunk a few feet away, penetrated to a depth of 2,406 feet.

(ii) The Langley Park Bore—depth 1,238 feet, situated a few hundred yards west of the Causeway, approximately two and one-quarter miles east of the King's Park Bore.

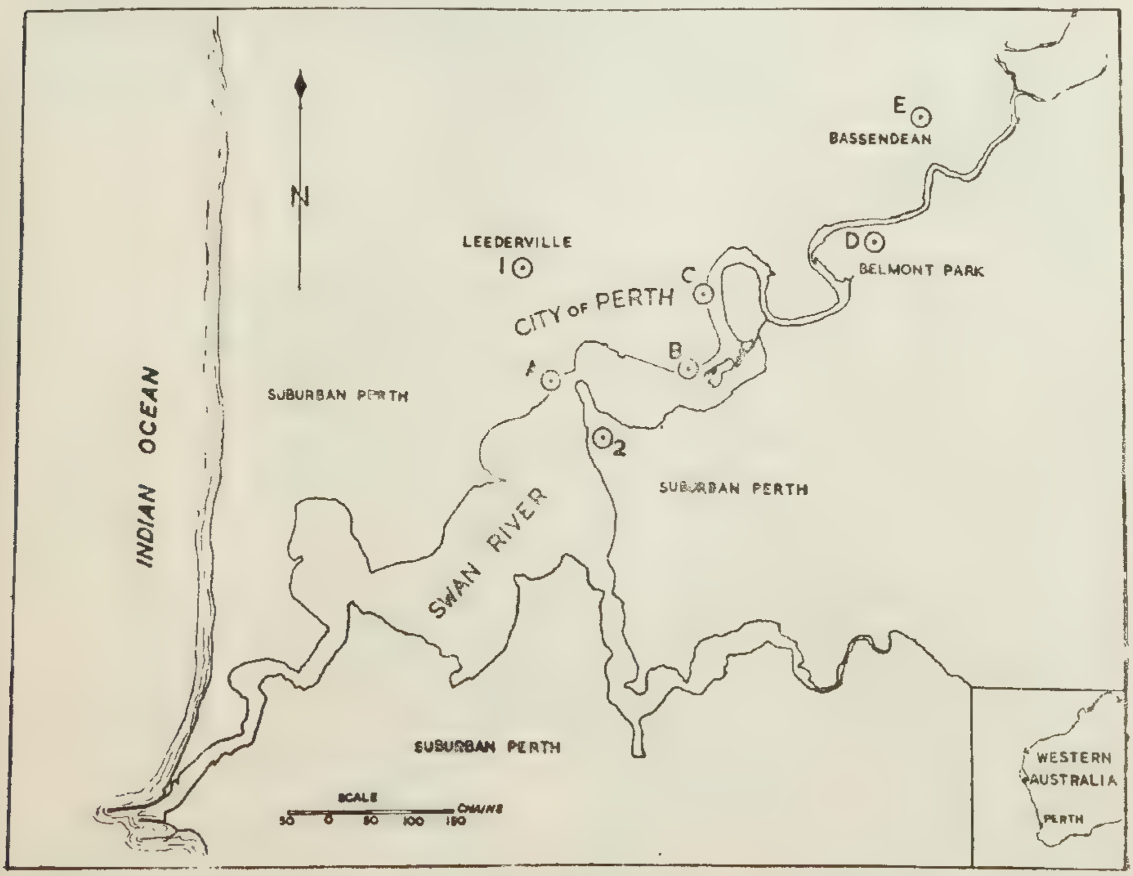
(iii) The Power House Bore—depth 1,300 feet, near the main Power House, one and one-eighth miles N.N.E. of the Langley Park Bore.

(iv) The Belmont Park Bore—depth 1,128 feet, at the Belmont Park Race Course, two and three-quarter miles E.N.E. of the Power House Bore.

(v) The Mt. Lyell Bore—depth 1,900 feet, at the production plant of Cuming, Smith and Mt. Lyell Fertiliser Company, Bassendean, about two miles N.N.E. of the Belmont Park Bore.

The bores, therefore, give a section approximately seven miles long, on a general line trending S.W.–N.E.

Text figure 2 gives the diagrammatic logs of the bores with the lithologic divisions. It can be seen that correlation based on lithologic grounds would be most uncertain.



Text fig. 1.

Locality map of the Bores: A—King's Park Nos. 1 and 2. B—Langley Park. C—Power House. D—Belmont Park. E—Mount Lyell. Also mentioned in the text were: 1—Leederville and 2—Zoological Gardens Bores.

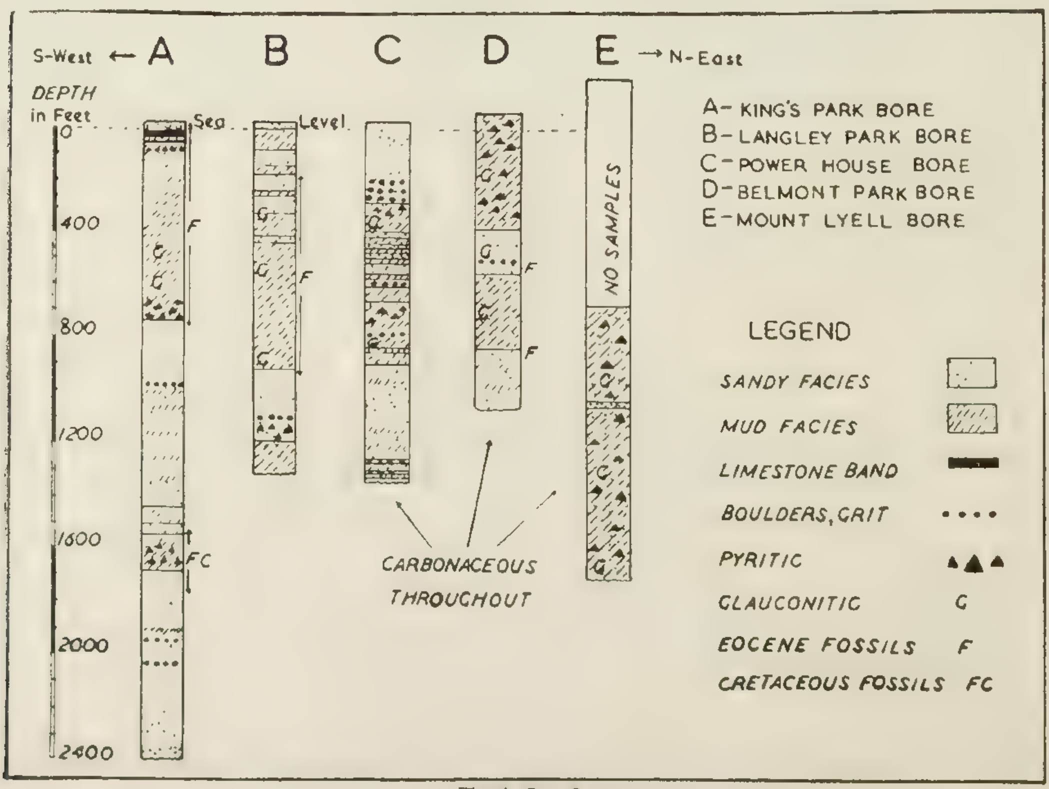
All five bores show a somewhat similar lithology. They pass through a surface sheet of recent sands and alluvium, then through a series of sands, sandstones, sandy shales, mudstones, in irregular succession, with coarse grits and gravel deposits (some representing the water horizons) at irregular intervals. The King's Park Bore passed through thin layers of limestone at the surface and at 84 feet.

Foraminifera were found in three only of the bores—the King's Park, the Langley Park, and the Belmont Park Bores. The Power House and Mt. Lyell Bores were unfossiliferous.

The fossiliferous material was a light grey fine shale or mudstone, at times rather sandy. Only when bit samples showed the unpulverised laminated shale fragments was it possible to decide definitely whether the material was shale or mudstone. It was noted in the Langley Park Bore that with an increase in sand content there was a corresponding diminution in the number of foraminifera. The shales of the Langley Park and Belmont Park Bores, particularly in the latter, were more sandy than those of the King's Park Bore.

This finer fossiliferous shale did not appear in either the Power House or Mt. Lyell Bores. Instead the shale or mudstone was very sandy, angular quartz grains predominating, was pyritic with sometimes a high proportion of glauconite, and generally contained a large amount of woody charcoal-like material. This sandy mudstone appeared in the non-fossiliferous portions of the other three bores.

Glauconite occurred in all the bores, but it was probably derived from some other older deposit. It was not at all fresh-looking, in rounded and sub-rounded grains, and only one recognisable cast was found. This seemed to be the cast of a minute gastropod, such as appeared in the Langley Park Bore—a simple spiral coil, only one complete whorl (the initial whorl) being preserved.



Text fig. 2.
Diagrammatic presentation of the lithology of the five bores examined.

DESCRIPTION OF THE FAUNA.

Foraminifera were found in the King's Park Bore between 0–84 feet (Recent-Pleistocene) and 84–780 feet (Eocene) and 1,535–1,770 feet (Cretaceous) ; in the Langley Park Bore between 10–90 feet (Pleistocene), and 208–975 feet (Eocene) ; and in the Belmont Park Bore at 530 feet, 840–900 feet, the foraminifera in this bore being very rare and poorly preserved.

Standard methods of procedure were used to extract the fossiliferous content of the samples. Flotation methods using a heavy liquid of bromoform and alcohol, specific gravity 2, gave excellent concentrates except for a few unsuitable samples.

The Eocene foraminiferal fauna was especially selected for study, both on account of its relative abundance and its unique position in the Australian sequence.

Fossils occurring in the residues were :—

(*a*) Foraminifera (most abundant).

(*b*) Sponge spicules (abundant).

(*c*) Ostracods—rare.

(*d*) Bryozoa—rare.

(*e*) Minute pelecypods and gastropods—rare.

(*f*) Echinoid spines—rare.

(*g*) Minute corals—extremely rare.

(*h*) Radiolaria—extremely rare.

The sponges are represented by several species :—

The genus *Geodia*—as white, reniform, spherical spicules abundant in the Langley and King's Park samples.

The genus *Geodites*—as white, annulated spicules, more restricted than *Geodia*. It is confined to the section below 375 feet in the King's Park Bore.

There are several other types, mainly represented by tetractinellid and lithistid spicules.

About ten different varieties of ostracods were met with including several species of *Cythere* and *Bairdia*.

Several types of minute gastropods were found, and in the Langley Park Bore a well preserved pelecypod, which persisted through many samples to a depth of about 600 feet.

The simple corals are minute and rarely well-preserved. The largest measured nearly three millimetres in length and one millimetre largest diameter. Through the agency of Dr. D. Carroll, then of the Geology Department, these were identified by Dr. J. W. Wells, of Ohio State University, as belonging to two species—*Trematrochus* sp. aff. *lateroplenus* Dennant, the other a new species, probably ? *Oculina* sp.. *Trematrochus lateroplenus* has been found previously in Southern Victoria in Balcombian strata at Shelford, Muddy Creek, Fishing Point, and Lower Moorabool, and in Janjukian strata at Spring Creek, Cape Otway, and Lake Alexandria (Wells, 1942). It has a known range, therefore, of Upper Oligocene to Lower Miocene. These corals were found in samples at 300–320 feet and from 400–440 feet in the Langley Park Bore.

Radiolaria occurred in a few samples in the three Bores.

Echinoid spines belonging to a single type were found in many samples from the Langley Park Bore.

Except in a few instances where the spicules of *Geodia* sp. outnumbered them, the foraminifera were by far the most abundant fossils found. They were mainly small, poorly preserved, and more or less typical of moderately deep water. Only six species approached or exceeded a millimetre in greatest dimension—notably :—

Cyclammina incisa (Stache).
Globulina rotundata (Bornemann).
Guttulina irregularis (D'Orb).
Lenticulina sp. II.
Nodosaria sp. aff. *raphanistrum* (Linne).
N. affinus (D'Orb).

Over ninety species of foraminifera were found in material from the three bores. Many of these are so rare or badly preserved that they are not recorded here. Those identified are :—

Alabamina obtusa var. *westraliensis* Parr.
Anomalina sp. I.
A. sp. II.
A. perthensis Parr.
A. pseudoconvexis Parr.
A. westraliensis Parr.
Angulogerina subangularis Parr.
Bathysiphon sp.
Bolivinopsis crespinae Parr.
Buliminella westraliensis Parr.
Cassidulina sp.
Ceratobulimina westraliensis Parr.
Cibicides lobatulus (Walker & Jacob).
C. umbonifer Parr.
C. sp. aff. *victoriensis* Chapman, Parr & Collins.
Cornuspira involvens (Reuss).
Cyclammina incisa (Stache).
Dentalina sp. I.
D. sp. II.
D. sp. III.
D. colei Cushman & Dusenbury.
Discorbis sp. I.
D. assulatus Cushman.
Dorothea sp.
Elphidium excavatum (Terquem).
E. sp. aff. *macellum* (Fichtel & Moll)
Epistomina elegans (D'Orb).
Eponides exiguus.
Frondicularia australis Herron-Allen and Earland.
F. sp. aff. *parkeri* Reuss.
Globigerina orbiformis (Cole).
G. mexicana (Cushman).
Globorotalia sp. I.
G. sp. II.
G. chapmani Parr.
Globulina sp. I.
G. gibba D'Orb.
G. rotundata (Bornemann).
Gumbelina venezuelana (Nuttal).
Guttulina irregularis (D'Orb).
Gyroidina soldanii (D'Orb).
G. soldanii var. *octocamerata* Cushman & G. D. Hanna.
Heronallenia pusilla Parr.
Hopkinsina sp. nov.
Lagena acuticosta Reuss.
L. luciae Parr.
L. orbignyana (Sequenza).
L. perthensis Parr.
L. squamosa (Montagu).
L. terrilli Parr.
L. sp. III.
Lenticulina rotulata (Lam).
L. sp. I.
L. sp. II.
L. sp. III.
L. sp. IV.
L. sp. V.
Marginulina sp. I.
M. gladius Philippi.
M. subbullata Hantken.
Nodosaria affinus (D'Orbigny).
N. ovicula.
N. radicula (Linné).
N. sp. aff. *raphanistrum.*
N. sp. IV.
Nonion novozealandicus Cushman.
Pattelina advena Cushman.
Pseudoglandulina clarkei Parr.
Quinqueloculina venusta Karrer.
Q. vulgaris D'Orb.
Q. seminulum (Linné).
Q. sp. IV.
Robulus warmani (Barbat & Von Estorff).
R. sp. II.
R. sp. III.
Robertina sp. I.
R. sp. aff. *convulata* (Will).
Strebleus beccarii (Linné).
Spiroplectammina sp.
Sigmomorphina sp.
Spirillina sp. I.
S. sp. II.
Vaginulina sp. I.
V. subplumoides Parr.
Vaginulinopsis sp.
Valvulineria sculpturata Cushman.
K_2 genus novus ?
AL_2 *Anomalina* sp.

The faunal assemblage as a whole is unlike that of any other region in Australia.

Most of the species are common to the King's Park and Langley Park Bores. Amongst them are *Hopkinsina* sp. (which according to Parr (personal communication) is possibly the first occurrence of this genus in Australia) an interesting species of *Globorotalia*, a species exhibiting unusual generic characters which may represent a new genus, and a puzzling species, possibly of the genus *Anomalina.*

It will be noted that some of the species recorded are unnamed and are suffixed by Roman numerals. This is a common practice for the purpose of local usage. Since the investigation was primarily of a stratigraphic nature no attempt was made to name them. Most of these species appear to be new and will be the subject of a later paper. Representative specimens of these and the named species are kept in the palaeontological collection of the Geology Department of the University of Western Australia.

COMPARISON OF THE KING'S PARK, LANGLEY PARK, AND BELMONT PARK BORES.

One of the objects of the investigation was to ascertain if a regular sequence of distinctive sections, based on foraminiferal evidence, could be recognised in the fossiliferous beds which the bores pierced.

As stated, only two of the bores yielded a vertical range of fossiliferous beds of reasonable thickness. The Belmont Park bore gave a seventy foot section from which a few species, too rare to be used for reliable correlation, were obtained.

Indications, gathered from a study of Parr's work (1938), that the bore sections could be subdivided into groups (Quarternary, Eocene and Cretaceous), characterised by definite assemblages were fulfilled when a general distribution chart was drawn from a study of the foraminifera yielded from the three bores.

Analysis of this general distribution chart showed :

(*a*) Those species which occurred throughout the sequence.

(*b*) Those that occurred through the greater part of it.

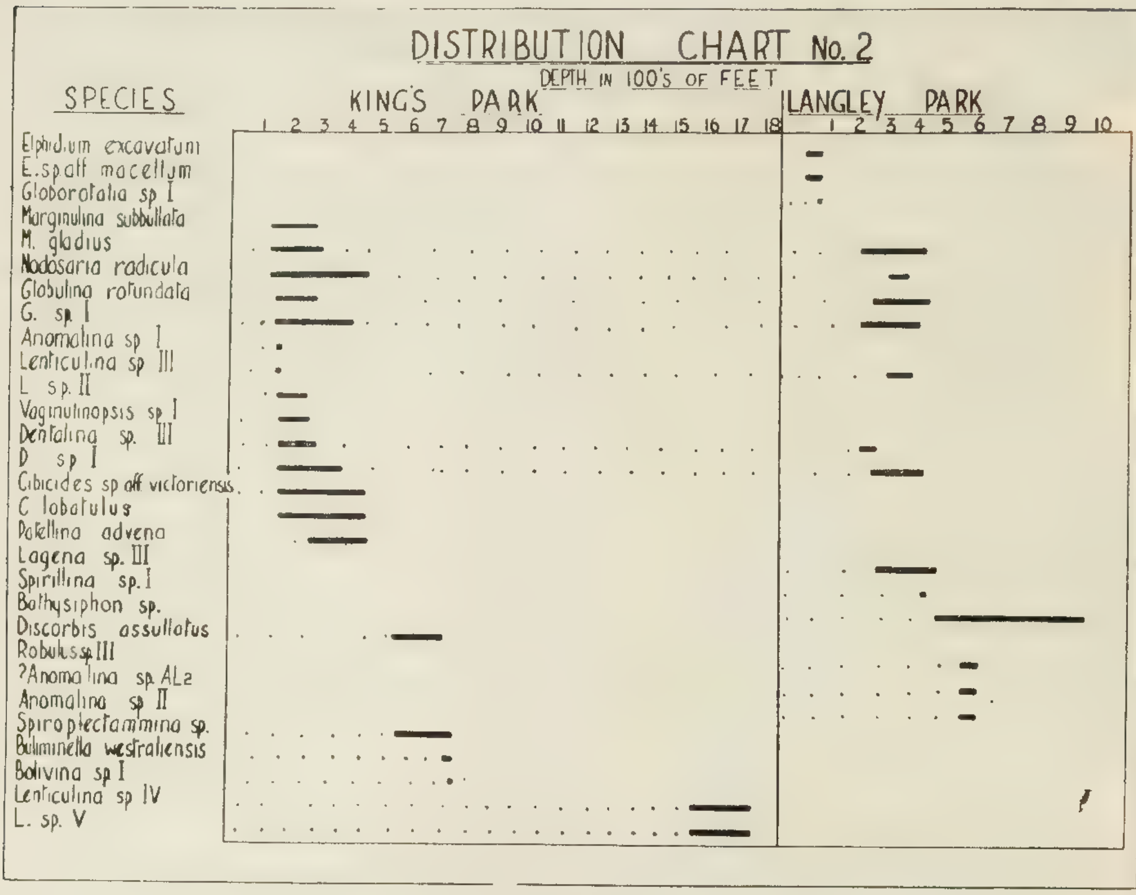
(*c*) Short-ranging species.

(*d*) Species with changing frequency.

(*e*) The distribution of accessory microfossils (ostracods, echinoid spines, minute corals and pelecypods, etc.).

Study of this chart revealed many species that were useless for subdividing the beds, *e.g.*, species that occurred through the sequence in practically the same frequency ; species occurring at rare intervals in varying frequency throughout the whole sequence ; species restricted to single samples. Rareness of a species was not regarded as a discouraging sign. Indeed many rare species are more useful than the more frequent ones. It must be noted that with the species of stratigraphic value are also found the many other " useless " species which tend to mask the presence of the fewer but more important forms, and hence the residues have to be examined with care.

Most of the species possessed little correlation value and so a second distribution chart was drawn up in which appear only those species thought to be of correlative value. Against each was plotted its frequency and occurrence, spaced to scale according to its stratigraphic range (*see* text fig. 3.)



Text fig. 3.

Distribution chart of those species considered to be of stratigraphic value, found in samples from the two bores which yielded foraminifera in any frequency.

Unfortunately some species that were of potential stratigraphic value, occurring frequently over a limited vertical range, were restricted to one bore and thus could not be used for correlation.

It was found that each bore could be divided roughly into bio-stratigraphic units, each characterised by :—

(*a*) index species—restricted forms, and those in which the maximum frequency coincides with the unit.

(*b*) Typical accessories whose first frequent occurrence marks the top of the unit.

(*c*) Accessory species which need not be restricted to the unit but which exhibit a characteristic frequency through the unit.

The samples, having come from percussion bores, and the chances of contamination being rather serious, only the first frequent appearance of the species (*i.e.*, in descending order in the section) could be used with certainty to define stratigraphic horizons. In some instances a species would occur frequently over a small vertical range and then some hundreds of feet lower, an isolated rare instance would be found. It was thought justifiable in such instances to more or less disregard the isolated rare occurrence.

Ecological questions did not enter very much into the problem of correlation, although what *is* known about the structure of the beds, their lenticular discontinuous nature, would suggest that in large-scale correlation in the future the ecological significance of the faunas discovered will have to be seriously considered.

From a study of this second distribution chart (text fig. 3) it is evident that the King's Park Bore can be subdivided into five bio-stratigraphic units :—

(1) A surface layer of Recent and Pleistocene coastal limestone, with very rare Recent and Pleistocene foraminifera, followed by unfossiliferous sand, clays, and bands of limestone, with a pebble conglomerate at 83 feet below the surface.

(2) Between 84 and 300 feet (Eocene)—characterised by *Anomalina* sp. I, *Lenticulina* sp. III, *Marginulina subbullata, Marginulina gladius, Globulina rotundata, Lenticulina* sp. *II, Vaginulinopsis* sp. I, *Dentalina* sp. III.

(3) Between 300 and 450 feet (Eocene)—characterised by *Patellina advena,* and overlapped between 100 and 450 feet, by *Globulina* sp. I, *Nodosaria radicula, Cibicides lobatulus.*

(4) Between 500 and 780 feet (Eocene)—by *Discorbis assulatus, Spiroplectammina* sp. I, *Buliminella westraliensis* (728–55 feet).

(5) Between 1,558 and 1,770 feet. This section produced only three species. *Lenticulina* sp. IV, *Lenticulina* sp. *V*, and *Dentalina* sp. aff. *colei.* It may be of Cretaceous age. (Note.—Lower Cretaceous foraminifera were found in the Leederville and Zoological Gardens Bores between 1,680–1,750 feet and 1,650–1,746 feet respectively.)

The Langley Park Bore can be similarly subdivided, but not so completely as the King's Park Bore, as follows :—

(1) From 0 to 70 feet strata containing Pleistocene foraminifera—*Elphidium* sp. aff. *macellum, E. excavatum, Strebleus beccarii,* also an unidentified *Globorotaliid.*

This is followed by 130 feet of unfossiliferous sands and clays.

(2) Between 200 and 450 feet—characterised by *Dentalina* sp. III, *Globulina* sp. I, *Marginulina gladius, Dentalina* sp. I, *Globulina rotundata, Lagena* sp. III, *Nodosaria radicula, Lenticulina* sp. III, and the lower by *Spirillina* sp. I.

(3) Between 660 and 603 feet—indicated by the presence of *Anomalina* sp. II, *Robulus* sp. III, and ? *Anomalina* sp. *AL_2*.

(4) From 470 to 951 feet characterised by *Bathysiphon* sp. in fair frequency.

The subdivision of the bores rests on the sum of species with comparatively short but overlapping ranges, rather than on restricted, disconnected, " characteristic " species. Unfortunately in both bores, between the third and fourth section in the King's Park, and second and third sections in the Langley Park Bore, there are no species which overlap from one to the other. In the Langley Park Bore, however, *Lagena acuticosta* shows a restricted increase in occurrence, between 450 and 555 feet.

It is immediately noticeable that species which are characteristic of a particular biostratigraphic unit in the King's Park Bore have much longer ranges or possess no stratigraphical value in the Langley Park Bore. Thus a biostratigraphic unit of the King's Park Bore is distinguished by the restricted occurrence of certain species which do not serve any such distinguishing purpose in the supposedly equivalent unit in the Langley Park Bore, and vice versa.

Since only two of the bores provided faunal data no explanation is offered to account for this fact. For the same reason it is not suggested that this would have been the case if a much larger number of bores had been studied. It suggests, however, that the Eocene beds may prove incapable of fine subdivision.

It is striking to notice the manner in which a high proportion of the species suddenly flash into prominence in both bores, *i.e.*, in the first fossiliferous samples after the surface material of Recent and Pleistocene age. This horizon, the top of the Upper Eocene, is at approximately 84 feet in the King's Park Bore, and 208 feet in the Langley Park Bore.

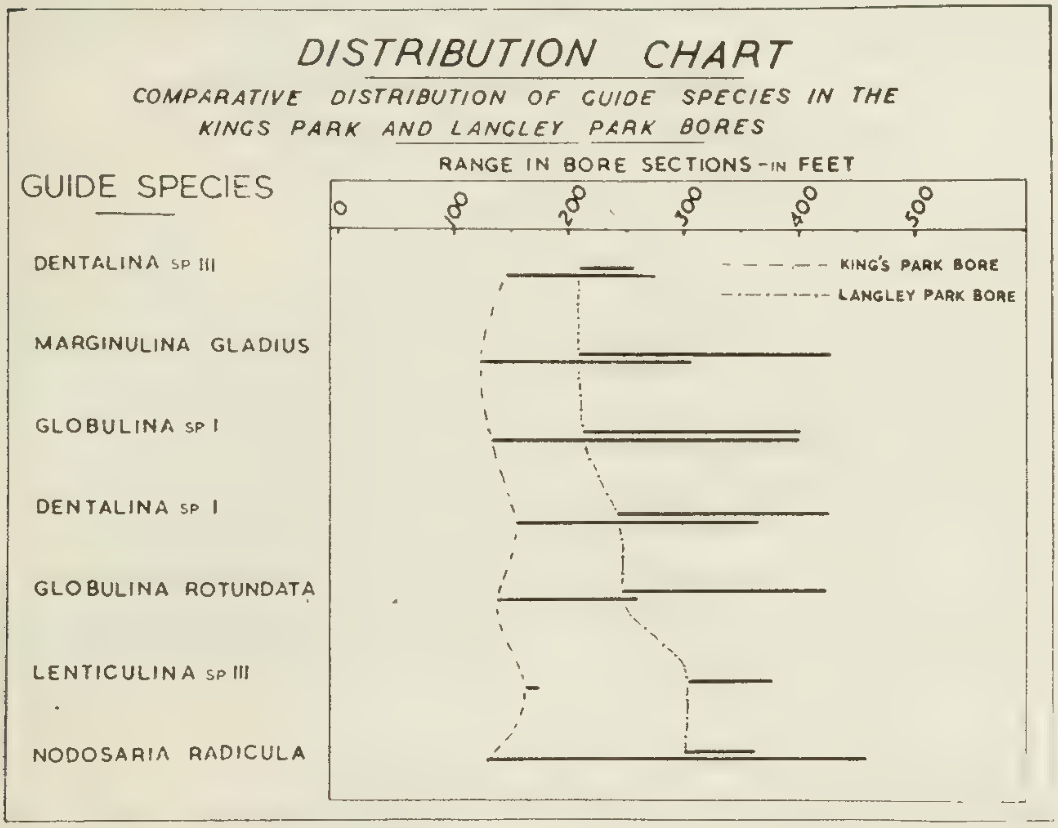
Only seven of the species of stratigraphic value are found common to both bores, which makes comparison of the two sections rather unsatisfactory. Probably many of the characteristic species peculiar to one bore could be found in the other, if searched for with extreme care. But the very necessity of a prolonged and careful search reduces their stratigraphic value.

A comparison chart (text fig. 4) was drawn showing the vertical ranges of these seven species in both bores. It can be seen that the lines joining the first frequent occurrences of the species are sub-parallel, and the mean vertical range between these lines is approximately 120 feet—the same figure as the difference in depth below the surface of the respective horizons which yield the first samples containing Eocene forms, namely, 84 feet in the King's Park Bore and 208 feet in the Langley Park Bore.

As the thickness of strata of Upper Eocene age is about the same in both bores, 770 feet in the Langley Park and 700 feet in the King's Park Bore, it would seem then that fossiliferous sections in the Langley Park Bore corresponding to those in the King's Park lie at a greater depth in the Langley Park Bore—approximately 120 feet deeper. This may indicate either a regional dip to the east for the fossiliferous strata, or the presence of a fault between the two sections. Further investigation of many more sections in the area is needed to confirm or refute this suggestion.

The Belmont Park Bore yielded 70 feet of fossiliferous material—between 830 and 900 feet, with an isolated sample at 530 feet. The foraminifera are rare and badly preserved, numbering only 17 species. It is impossible to correlate this short section with the other bores. For the most part it penetrated lithologically similar beds to the Power House Bore, about three miles to the west. It seems strange to find one bore with a comparatively abundant fauna over a vertical distance of 770 feet, and another only a mile away, completely barren of fossils and differing greatly in the lithology of the beds passed through. Thus the Langley Park Bore is fossiliferous, particularly between 208 and 975 feet, and then passes through unfossiliferous very sandy mudstone for nearly 600 feet. On the other hand, the Power House Bore only one and one-eighth miles to the N.N.E. passes through pyritic and carbonaceous sandy mudstones for its entire depth of 1,200 feet, and is completely unfossiliferous. These differences suggest that the sediments of the

Power House Bore were laid down in an area not directly connected with the sea, *i.e.*, they are of lagoonal or barred basin facies whereas the sediments of the Langley Park Bore are in part of true marine origin and in part of possibly lagoonal origin.



Text fig. 4.
Species of stratigraphic value common to the King's Park and Langley Park Bores. Arranged in order of first appearance in the Langley Park Bore.

From the analysis of material from these bores and examination of drillers' logs of bores throughout the whole area it seems that fossiliferous strata will be found at depths less than about 2,000 feet only to the west of a line trending approximately north-south through the Power House Bore.

The lithology of the strata through which the bores pass is of little help in correlation. It is interesting, nevertheless, to note the manner in which the foram-bearing shales and mudstones gradually increase in sand content from the west (the King's Park Bore) to the east (the Belmont Park Bore), followed then by unfossiliferous freshwater strata still further to the east, which may indicate a gradual approach to shore-line conditions.

CONCLUSIONS.

Although only two of the five bores examined yielded foraminifera over a vertical range exceeding 100 feet certain general conclusions and indications for future work can be drawn from this study. The King's Park, Langley Park, and Belmont Park Bores pass through strata with similar faunas to

those previously described by Parr (1938) as Upper Eocene* and the foraminifera may be used for correlating these strata. The lithology of the bores was of little use in correlation. The study has emphasised the need for the proper collection of samples from future bores.

Insufficient data are available for estimating closely the prospects of correlating and ascertaining the structure of the beds beneath Perth by means of the foraminifera. The fact mentioned above, that bores in the western part of the basin can be broadly correlated is promising, but this is counterbalanced by the puzzling, sudden absence of fossils in those bores east of the Power House.

ACKNOWLEDGMENTS.

I wish to accord my sincere thanks to the many who have helped me so considerably in both the preparation and completion of this work. They include Professor E. de C. Clarke, Professor R. T. Prider, and Dr. R. W. Fairbridge, of the Geology Department of the University of Western Australia, who at all times were only too ready to help with advice and direction. Also the late Mr. W. J. Parr, of Melbourne, who identified many of the species found, and supplied me with helpful suggestion and advice.

Again, I would take this opportunity of expressing my gratitude to Miss Irene Crespin, the late Dr. J. A. Cushman, Massachussetts, U.S.A., and in a special manner, to Mr. H. J. Smith of the Geology Department of the University of Western Australia, for their support, encouragement, and assistance in numerous other ways.

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* Further evidence as regards the age of this fauna has recently come to hand. Miss I. Crespin, Commonwealth Palaeontologist, has kindly drawn the attention of the writer to a paper by F. Brotzen (Sveriges Geologiska Undersokning, Ser. C. No. 493, Arsbok 42, No. 2, 1948), in which a closely similar fauna from the Paleocene of Sweden is described. Brotzen has indicated the close relationship between this in turn, and the foraminiferal fauna of the Midway Group of Alabama, upon which the late Mr. W. J. Parr had largely based his original correlation. It is probable then that at least part of the fauna of the Perth basin hitherto assigned to the Upper Eocene, is of Paleocene age.

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4.—THE GEOLOGY OF THE HAMERSLEY SIDING AREA

By

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Communicated by Professor R. T. Prider, 9th May, 1950.

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ABSTRACT.

The country near Hamersley Siding, N.W. of York, is underlain by Pre-Cambrian metamorphic rocks. The main type is a microcline-oligoclase gneiss with which are intercalated two bands of coarse-grained quartzite containing chrome-muscovite. With the latter are lenses of other metamorphic rocks—plagioclase amphibolites; hypersthene, cummingtonite, and grunerite metajaspilites; and sillimanite-garnet-cordierite-anthophyllite rocks. These lenses are explained as the metamorphic equivalents of limestones, shales, cherts and sandstones in a great thickness of arkose, now represented by the gneiss itself.

Near the west side of the area, a granite mass is emplaced, causing a felspathisation of nearby gneiss. Granite dykes also traverse the metamorphics. Associated with the granite, and intrusive into both granite and gneiss, are appinites or hornblende granites—a rock type whose intrusive relationships have not been noted in Western Australia before. The last phase of igneous activity is represented by dolerite dykes.

The structure, as shown by the two bands of quartzite, is interpreted as a large anticlinal box-fold which pitches to the south.

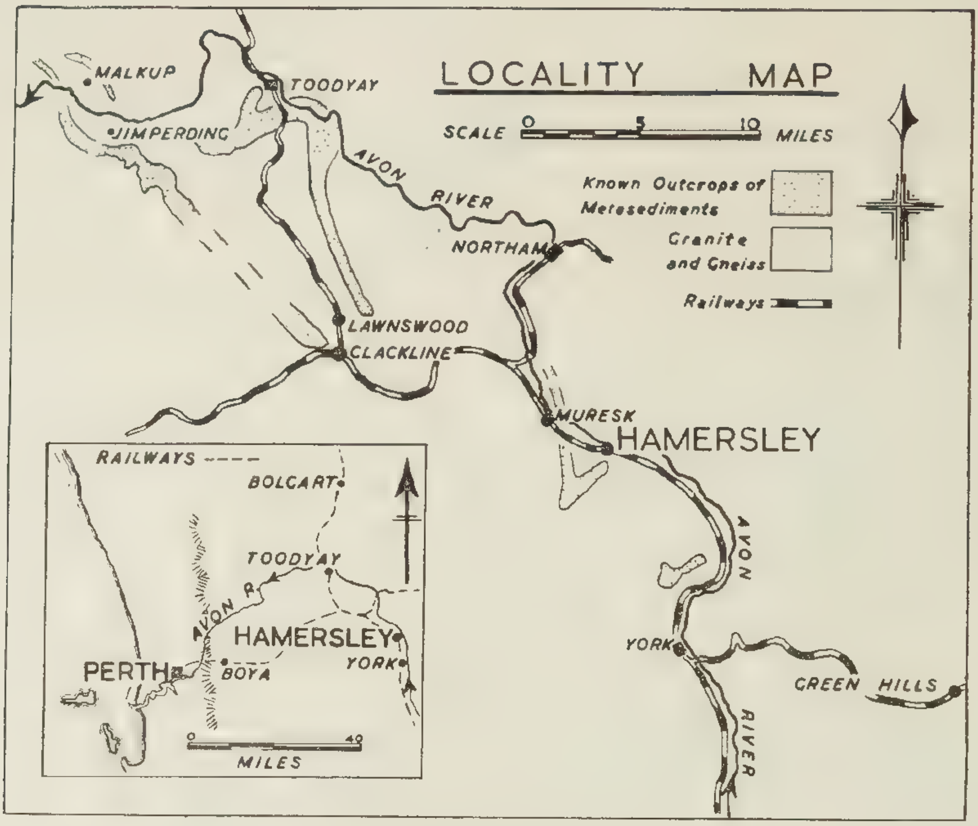
I. INTRODUCTION.

Hamersley Siding, which lies in the north-east corner of the area under review, is situated eight miles north-west of York, and the area mapped in 1948–49 measures 5 x 4 miles. It comprises the major part of three mixed farming properties which lie in the Avon Valley, a tract of highly productive agricultural land, which extends from Pingelly to Toodyay.

The region is part of the ancient West Australian Shield and contains gneisses, schists and quartzites of early Pre-Cambrian age. The accompanying map (text fig. 1) shows that the metasediments of the Hamersley Area are not structurally continuous with those of the Jimperding Series which outcrop at Jimperding (Prider, 1934), Toodyay (Prider, 1944) and Lawnswood (McWhae, 1948); but although these rocks may be lower or higher in the sequence than those of the Jimperding Series, I propose to tentatively class them as part of that series.

The field survey was undertaken by parties of students from the Geology Department of the University of Western Australia, during 1948 and 1949. Chain and compass traverses, linked to a framework of road pegs and boundary fences surveyed by the Lands and Survey Department, formed the basis of the mapping.

Major topographic features—the laterite mesas to the west of the area and the main stream courses—were mapped from aerial photographs taken by the R.A.A.F.



Text Figure 1.

Map of localities mentioned in the text.

Grateful acknowledgment for supervision of this work is due to Professor R. T. Prider and Messrs. A. F. Wilson and W. A. J. Saunders of the Geology Department of the University of Western Australia ; to many students of that department for assistance with the mapping and in the preparation of thin sections ; also to Mr. H. J. Smith for the photomicrographs ; and to Mr. A. D. Hosking and Mr. J. Lorimer for the photographs in Plate III. Thanks are due also to Mr. Edward Hamersley, of Hamersley Siding, for permission to work and camp on his property. Assistance received from the Government Research Grant to Universities is also gratefully acknowledged.

II. PHYSIOGRAPHY.

The area contains many of the features characteristic of the peneplained surface of the Western Australian Shield—the laterite hills of the Darling Ranges, and the gentle, undulating granite and gneiss country of the Wheat Belt. To the South and West, the area is bounded by partially dissected laterite mesas—remnants of the " Old Plateau." The northern and eastern boundaries lie in the broad, fertile, much-cultivated, valley of the Avon River. The land falls from the south and west to the north-east, and the main drainage follows this fall. The drainage channels may be classified into two groups :—

1. Short, intermittently-flowing, streams which head at the margin of the Avon Valley and flow directly down the valley sides into the river.

2. The major interior drainage of the area formed by Heale Brook (called Brekna Brook on the one-inch military map—York sheet) and its tributaries. The stream pattern here is closely related to the linear structures in the gneiss and quartzite (Plate I). Heale Brook crosses the area from south-west to north-east where it joins the Avon, being joined by Cobham Brook from the south-south-east. It is a rather unusual stream for this area in that it flows continuously throughout the year.

Four small residual hills of laterite remain in the centre of the area. These, like the laterites at Lawnswood (McWhae, 1948, p. 51) have sloping, not horizontal, tops ; but the dips on the laterites here are smaller than those in the Lawnswood area, averaging 4°.

The topography and soil are closely related to the two main rock-types—quartzite and gneiss. The gently-rolling gneiss country has but sparse outcrops and is cleared and cultivated. Quartzites, being more resistant, stand above the general level as hills with blocky outcrops and steep talus slopes.

In the central part of the area, where the quartzites strike north-east, the relief is such that strike and dip readings could be made, but elsewhere the " outcrops " consisted merely of boulders protruding from the soil.

Characteristic flora distinguish the main rock and soil types. The areas of gneiss support York Gum (*Eucalyptus foecunda*, var. *loxopheba*) and Jam (*Acacia acuminata*). Wandoo (*E. redunca*, var. *elata*) marks the quartzite and schist areas largely to the exclusion of York Gum and Jam.

III. FIELD DISTRIBUTION.

Most of the country (adjacent to Hamersley Siding) is underlain by a hybrid microcline-oligoclase-biotite gneiss. Interbedded with the gneiss, two discontinuous bands of quartzite, striking north-north-west, outcrop along the western margin of the area from the extreme north-west corner to (60N, 340W)*. Here, the strike changes abruptly to north-east and the rocks outcrop in this direction for 2½ miles, ending in a series of well-bedded quartzites and schists at Mt. Mackie. Paralleling the quartzite bands there are groups of metasedimentary lenses in the gneiss. These consist chiefly of plagioclase amphibolites, metajaspilites and garnet-cordierite-anthophyllite rocks.

In the central-western part of the area, a small body of fine-grained, massive granite outcrops. The granite and also its associated appinites are found as dykes of varying size traversing the gneiss.

The dolerites occur in several sets of dykes, the most prominent of which have a north-north-west trend. One large dyke of this group can be traced for a distance of 5 miles crossing the area from the north-west to the south-east corner. Minor fractures trending north-east and west-north-west are also occupied by dolerites.

Later superficial deposits consist of the laterite capping of a few small hills and the alluvium in the valleys of Heale Brook and the Avon River.

* Co-ordinates for the Hamersley Siding Area are measured in chains from the north-east corner of Block Y8 on the Lands Department Litho.

IV. PETROLOGY.

A. PETROGRAPHY.

1. Gneisses and Associated Rocks.

(a) *Gneisses.*

The common hybrid gneiss is a medium-grained, uniformly banded, slightly porphyritic, microcline gneiss.

This gneiss is locally interbanded with aplitic and basic types, notably at a waterfall at (128N, 231½W) in Cobham Brook. Small basic patches of garnet-biotite gneiss occur in other phases of the complex. Microscopic examination revealed further variations; aplitic gneiss rich in microcline, pure oligoclase-quartz gneiss, or variations between these two. The microcline-oligoclase-biotite gneisses often contain porphyroblasts of pink garnet surrounded by clots of biotite flakes. The number of types developed and the sudden transformation from one variety to another illustrates the hybrid nature of the rock.

The gneisses are variable in grain-size, as well as in chemical and mineralogical composition Interbedded with the medium-grained gneisses described above are fine-grained and finely banded metasedimentary types.

Variants of the gneiss are:—

(i) Microcline-oligoclase-biotite gneiss (25552)*.—This contains porphyroblasts of microcline up to 14 mm. in diameter set in a groundmass of smaller grains (1 to 2 mm. diameter) of microcline, albite-oligoclase, biotite, muscovite and quartz. The porphyroblasts are firmly intergrown with the groundmass and show no signs of post-crystallisation granulation. They consist of microcline with perthitic intergrowths of albite. Myrmekitic inclusions of quartz have developed in crystals of oligoclase by reaction with adjoining crystals of microcline during recrystallisation. Although the microcline is clear and unaltered, the oligoclase has a turbid appearance due to alteration to a fine aggregate of sericitic mica. Apparently the parent rock contained potash in excess of the amount required to satisfy all the microcline and biotite present. The oligoclase, at first, absorbed this excess potash into its own crystal lattice, but later the combination became unstable and the oligoclase disgorged its potash as a white sericitic mica. Quartz occurs in anhedral form amongst the microcline and oligoclase but also as small, round grains included in crystals of the felspars—possibly relics of original sand grains in the parent sediment. The biotite (X yellow, Z brownish-black) occurs in stout laths and shows incipient alteration to chlorite which gives it a greenish tinge. Associated with the biotite are plates of muscovite of comparable size (½ x 1 mm.).

(ii) Oligoclase-biotite gneiss (25597).—Although lacking in microcline this gneiss is not basic, but rather tends towards the aplitic type.

The handspecimen, collected at the waterfall in Cobham Brook, shows the hybrid nature of these rocks. Parts of the specimen are pure aplite (containing only oligoclase and quartz) whereas other parts contain up to 50 per cent. of garnet and biotite. The rock is traversed by several epidote veins near which the alteration of biotite to chlorite is almost complete; within 1 cm. of the veins the oligoclase undergoes saussuritisation instead of the usual sericitisation which prevails elsewhere.

* Numbers in parenthesis refer to specimens in the collection of the Department of Geology, University of Western Australia.

(iii) Garnet-biotite gneiss (25589),—These rocks occur as very fine-grained ($\frac{1}{4}$–$\frac{1}{2}$ mm.) lenses in the microcline and oligoclase gneisses. They have an equigranular granulitic texture developed in abundant grains of pink garnet (35 per cent.) and quartz (30 per cent). Their banded appearance is due to alignment of the flakes of brown biotite which form 15 per cent of the rock ; sericitised oligoclase makes up the remainder.

(iv) Graphite-bearing gneiss (24655),—The only specimen of this rock-type comes from the kaolinised zone near one of the central laterite mesas. Although the graphite remains unaltered, the original felspars and ferromagnesians have been converted to kaolinite minerals. Bands of these minerals alternate with thin quartz and graphite bands in which the graphite is in well-developed flakes $\frac{1}{2}$ mm. in diameter.

(v) Crush-Zone " Quartzites" (30029).—Certain highly-quartzose rocks occur in isolated outcrops which are not structurally related to the two bands of quartzite. They are not bedded and have a milky appearance caused by the fineness of the quartz grains. The quartz appeared either to have been crushed or to have crystallised under shearing conditions. The type specimen (30029), shows irregularly-shaped inclusions of gneiss amongst the fine-grained quartz ; so the rock must represent a crush-zone in the gneiss. A line of these lenses points to a possible major shear in one part of the area.

(b) *Pegmatites.*

(i) Microcline-biotite pegmatites.—In some places the gneiss is traversed by coarse-grained pegmatite dykes. Specimen (25558) contains crystals of microcline 3 inches long and books of biotite 1$\frac{1}{2}$ inches long set in a matrix of quartz. No accessory minerals are visible in this dyke whose dominant minerals belong to the same metamorphic facies as the enclosing gneiss.

Common throughout the area are finer-grained pegmatites in narrow veins 2 inches wide. These, containing grains of biotite, microcline, oligoclase and quartz up to 4 mm. in diameter, are found transgressing the gneiss (25553), and the metasediments (25561). Apparently the nature of the host rock affects the composition of the vein for (25561), traversing a chrome-muscovite quartzite, contains muscovite, oligoclase and quartz.

These pegmatites are pre-granite in age for they are displaced by the granite intrusions.

(ii) Quartz-pyrite vein (25570).—In the southern part of the Mt. Mackie area there occurs a coarse-grained quartz-pyrite vein. Cubic crystals of pyrite, with striated faces up to a square inch in area, are set in a groundmass of quartz. In the weathered outcrop, the pyrite has either been completely leached out or converted to limonite. The relationship of this vein to the gneiss, the granite, or the dolerites is uncertain, but it is probably connected with the pegmatites. The coarseness of grain size suggests that it was, like them, a locus of high ionic mobility.

(c) *Lenses in the Gneiss.*

Apart from the somewhat lenticular quartzite bands, there are also less regular lenses in the gneiss, which sometimes contain sedimentary banding ; structures developed in them are conformable with those in the quartzite bands. They include :—

(i) Metajaspilites.—These finely-banded metasediments are well developed in lenses throughout the gneiss (See under section IV, 2 : Metasedimentary Bands).

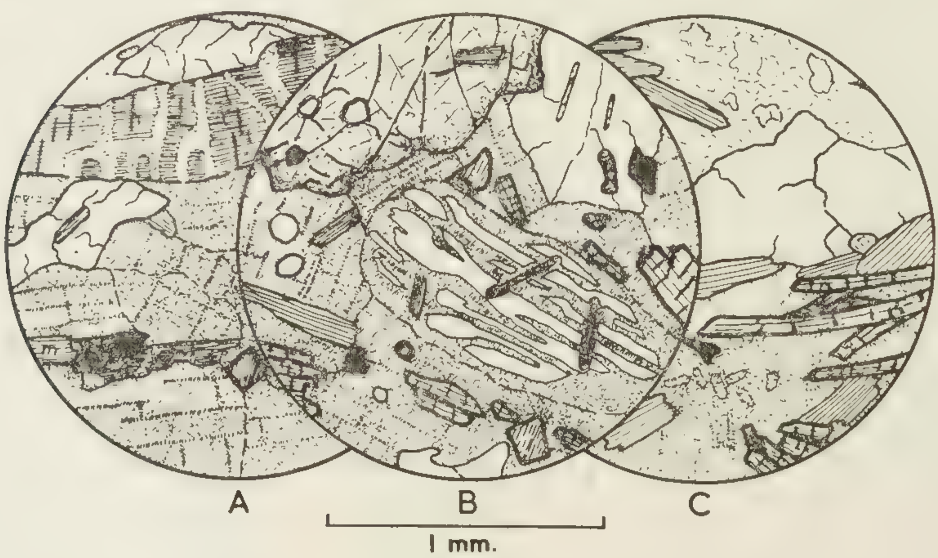
(ii) Hornblende granulites.—Containing small (1 mm.), equidimensional grains of hornblende, plagioclase and quartz, these typically sugary rocks show variations in colour from grey to black, depending on the percentage of hornblende present.

The hornblende commonly developed is strongly pleochroic with X yellow, Y deep olive green, Z deep green (Z>Y>X). Although most specimens show division into hornblende-rich and plagioclase-rich bands, in some only a preferred orientation of the prism cleavages of the hornblende crystals gives the rock its foliation.

The nature of the plagioclase varies, the most common being an andesine which may, or may not, be associated with quartz. Common accessories are magnetite and sphene. The type specimen (25554) contains andesine-labradorite, a blue hornblende (X light yellow-brown, Y deep olive green, Z deep blue (Y>Z>X)) and a diopsidic augite. A much more sodic phase is shown by (25579) which contains hornblende, an albite-oligoclase and quartz.

(iii) Garnet-biotite-sillimanite-cordierite-anthophyllite rocks represent basic lenses in the original sediments. They are dark grey to black in colour, due to the presence of biotite. The cordierite gives to the rocks its characteristic greasy appearance but most noticeable of all are large, pink garnets.

In thin section the latter sometimes appear as large, well-developed idioblasts containing poikiloblastic inclusions of quartz, cordierite, magnetite and biotite ; in other specimens are aggregates of irregularly shaped garnet crystals, separated by small crystals of quartz or cordierite.



Text Figure 2.

Garnet-biotite-sillimanite-cordierite-anthophyllite-rocks.

A. 25563. Anthophyllite-rich specimen. The anthophyllite is in stout laths with a well-developed cleavage; it is showing alteration to a fine, fibrous, orthorhombic mineral. Biotite (good cleavage), quartz (clear), and muscovite (m) are minor constituents. The groundmass is pinitised cordierite. A rhomb-shaped end-section of sillimanite occurs in the lower part of the field.

B. 25572. Variety with partially altered cordierite—a large crystal in the centre of the field shows partial alteration to pinite along cleavages. The cordierite contains poikiloblastic inclusions of cross-fractured prisms of sillimanite, together with quartz (clear), biotite (cleavage), zircon (rounded, high relief) and magnetite. The edge of a large garnet idioblast occurs at the top of the field.

C. 25385. Oligoclase-cordierite rock. Partially sericitised oligoclase (top) occurs with biotite, quartz, sillimanite (in cross-fractured needles with righ relief) and pinitised cordierite.

Quartz-rich and cordierite-rich layers produce a rough banding. The quartz occurs in long irregular stringers in a mass of cordierite. Embedded in the quartz are small needles of sillimanite (var. fibrolite) ; associated with both the cordierite and quartz are stout prisms of sillimanite, basal sections of which give (+) 2V = 26° (Text fig. 2B).

Cordierite, completely altered to a yellow-brown mass of brightly-polarising pinite (sericite mica), comprises nearly 40 per cent of most specimens. The cordierite contains most of the other minerals as poikiloblastic inclusions, notably flakes of brown biotite (X yellow, Y chestnut brown, Z deep chestnut brown), magnetite and rounded grains of quartz. In only one specimen (25572) is any recognisable amount of unaltered cordierite found ; its weakly-birefringent crystals showing hydration, along cleavage planes and other lines of weakness, to yellowish pinite (fig. 2B). A basal section of one crystal shows polysynthetic twinning in two planes set 60° apart.

Occasionally associated with the cordierite are large (½ mm. x 1½ mm.) colourless prisms of an orthorhombic mineral with well developed prism cleavages—an anthophyllite. This mineral, which is often associated with muscovite, is partially, or sometimes wholly, altered to a fibrous orthorhombic mineral with low relief and high birefringence (text fig. 2A).

In the acid members of this type, the garnet does not develop ; instead, bands of quartz and oligoclase occur amongst the bands of cordierite and biotite. In (25385), the oligoclase is altered to a sericite, distinguished from the pinite by its grey colour and coarseness of grain (text fig. 2C). In the most acid member (25168), which is an oligoclase-biotite-cordierite gneiss, the oligoclase-quartz bands are more abundant than the basic bands and the oligoclase is only partly sericitised (as it is in the gneisses).

2. Metasedimentary Bands.

(a) *Schists.*

Mica schists are not abundant since they are easily weathered. Nevertheless, sands and cherts predominated over clayey rocks in the original succession.

(i) Garnet-sillimanite-muscovite schist.—Scattered outcrops of sillimanite-muscovite-quartz schist and garnet-muscovite-quartz schist occur in the bands of metasediments near the stretch-thrusts at (80N, 340W), in the western belt of metasediments, and near Mt. Mackie.

(ii) Kyanite-anthophyllite schist (25401). This specimen, from the western limb of the main fold, shows a marked parallelism of coarse crystals (up to 7 mm. long) of blue-green kyanite. These have an extinction angle of 30°, a well-developed prism cleavage, and an imperfect cross-parting. Bands of muscovite and kyanite, which form 50 per cent of the rock, alternate with quartzose bands containing colourless orthorhombic prisms of anthophyllite.

(b) *Quartzites.*

Most of the quartzites show a green colouration due to chrome-mica flakes. The percentage of mica varies considerably in the different lenses,

from only a trace up to 20 per cent. or more, *e.g.*, (25379), which is strongly green in colour. The coarse-grained quartzites, although greenish in colour, show very little chrome-muscovite, none being seen in thin section.

(i) Felspathic quartzite (24661).—This is a coarsely crystalline rock comprised almost entirely of an interlocking mosaic of quartz grains up to 5 mm. in diameter. The only other mineral is microcline in rounded turbid grains—apparently a few detrital grains deposited in the otherwise pure sandstone from which this rock was formed. With admixtures of clay in the original sandstone, sillimanite needles formed within the quartz grains and the rock grades into the garnet-sillimanite quartzite group.

If subjected to shearing stress after recrystallation, these coarse-grained brittle rocks show marked cataclastic sturctures. One such (24651), found near the thrust-plane at Mt. Mackie shows the breakdown of a large quartz crystal into a fine micro-crystalline groundmass (Plate II (a)). Due to strain effects accompanying the shearing, the crystal shows marked undulose extinction.

(ii) Garnet-sillimanite quartzite (25411).—In this quartz-rich rock, the original bedding planes are now composed of a felted mass of needles of sillimanite (var. fibrolite). Small idioblastic garnets, up to 3 mm. in diameter, are abundant throughout.

Under the microscope, the sillimanite needles are seen to be embedded in an interlocking mosaic of quartz crystals. This type thus represents a transition from the pure quartzites with increasing alumina. A further increase of alumina produces the garnet-sillimanite-quartz schists found at Mt. Mackie. The garnets in this rock-type have been weathered out, leaving well-developed limonite boxwork structures.

(iii) Chrome-muscovite quartzite (25379).—This shows a marked development of green chrome-mica. Elongation of quartz grains and this mica on the bedding planes produces a marked *b*-lineation parallel to the *b*-tectonic axis. The rock was in a very plastic state when this lineation formed, for, in this specimen, the quartz grains have been drawn out into thin wisps parallel to *b* without showing undulose extinction or other signs of strain (Plate II b). The quartz grains are interbanded with flakes of a white mica which is altering to a fine-grained aggregate of pale green mica. This mica is comparable to that already described from Toodyay (Prider, 1944, p. 32). Needles of sillimanite and grains of zircon and rutile occur as inclusions in the quartz grains and in the mica. Both the sillimanite and the rutile are elongated parallel to *b*.

(c) *Metajaspilites.*

Because of their fine banding and numerous slump structures, these iron-rich rocks are considered to be metamorphosed cherts. Some types, however, represent recrystallised ferruginous sandstones and clayey ferruginous sandstones.

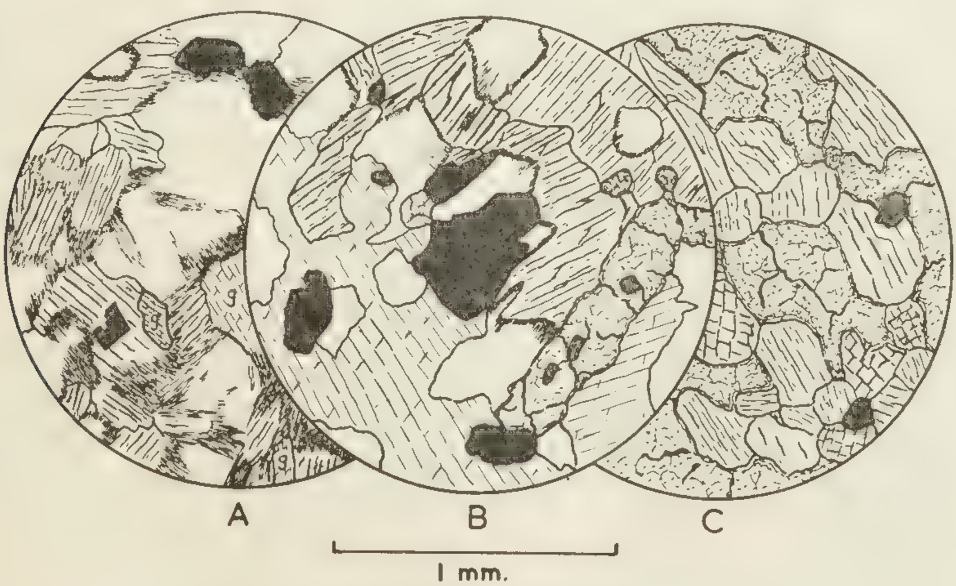
Near Hamersley Siding, the metajaspilites are found as numerous scattered lenses in the gneiss and as close associates of the quartzite bands into which they sometimes grade. They have their maximum development to the southwest of Mt. Mackie where a variety of types occurs. A thin veneer of iron-

rich laterite, similar to the iron ore deposits at Clackline which yield 45.5 per cent of iron (McWhae, 1498, p. 72), has formed over the greater part of this mass of metajaspilite.

(i) Magnetite quartzite (25583).—The quartzites grade, both along and across the strike, into ferruginous quartzites which consist of alternating bands of coarse granular quartzite and bands made up of small (1 mm.) equidimensional grains of quartz and magnetite. Although quartz predominates in this rock-type, its division into marked quartzose and iron-rich bands indicates classification as a metajaspilite. This is supported by the presence in (25581), of small weathered grains of pyroxene, indicating a transitional phase between the magnetite quartzites and the garnet-hypersthene-magnetite-quartz granulites.

(ii) Garnet-hypersthene-magnetite-quartz granulites.—These rock-types are all characterised by a granoblastic texture and by relict sedimentary bedding, now shown by variations in the mineral content of neighbouring bands which vary in width from 1 mm. to 1 cm.

A variety of types is included in this group. Some are so rich in quartz that they may be called pyroxene quartzites; in others quartz occurs in relatively few layers, the major part of the rocks being garnet hypersthenite. Magnetite and hypersthene are present in all examples, but the proportions of quartz and garnet are apparently inverse, the quartzose members being free of garnet while the garnet-rich members are almost completely free of quartz.



Text Figure 3.

Garnet-hypersthene-magnetite-quartz granulites.

A. 24662. A granoblastic aggregate of hyersthene (coarse cleavage), gunerite (g), magnetite (black) and quartz (clear). The grunerite and hypersthene grains show alteration, along their margins, to fibrous ferroanthophyllite.

B. 25404. The hypersthene (coarse cleavage) shows an alteration to ferroanthophyllite when in contact with quartz. Grunerite (fine cleavage) shows no reaction. Garnet (high relief) makes its appearance in the series. Magnetite is present.

C. 25448. A granoblastic aggregate of garnet (high relief) and hypersthene (cleavage). Magnetite (black) is accessory.

Since quartz forms 50 per cent of (24662), it could be called a hypersthene quartzite. It forms the link between the magnetite quartzites and the hypersthene-garnet granulites. Miles (1947 (a), p. 138) mentions a similar

rock, containing also plagioclase and biotite, from the vicinity of Mt. Bakewell, York. Specimen (24662) contains bands of coarse crystals of quartz up to 5 mm. in diameter alternating with fine-grained ($\frac{1}{2}$ mm.) granulitic bands of quartz, magnetite and hypersthene (X yellow, Z pale green). Associated with the hypersthene are occasional grains of twinned highly birefringent grunerite (text fig. 3A). Both the hypersthene and the grunerite have reacted with the quartz to give fine needle-like crystals of ferroanthophyllite. Similar alteration of hypersthene to ferroanthophyllite was noted in meta-jaspilites from Bolgart (Miles, 1947 (a), p. 136). These fibres are oriented parallel to the crystals of hypersthene and grunerite, which they enclose, and appear to be formed at the expense of the major ferromagnesians.

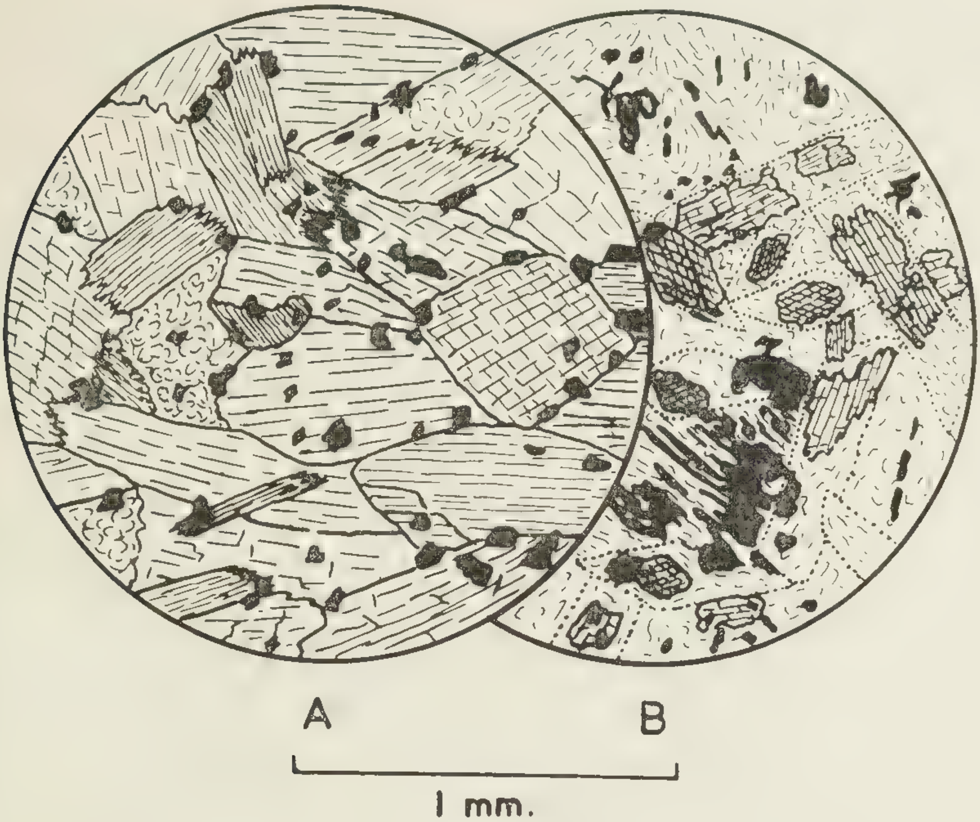
All stages between this quartzose type and the garnet-rich types are found. (25404) is an example of these intermediary rocks (text fig. 3B). It contains large crystals of grunerite and hypersthene in association with magnetite, quartz and pink garnet. The hypersthene shows the same fibrous alteration product as seen in (24662). Miles (1947, (a) p. 138) describes a similar rock-type from Bolgart, the fibres of which show variations in mineral type between ferroanthophyllite and a cummingtonite-grunerite.

A garnet-rich variant (25448), contains quartz in a few widely-scattered bands while the major part is a garnet hypersthenite (text fig. 3C). Bands of pure hypersthene granulite up to 8 mm. wide alternate with bands, 6 mm. wide, of garnet and hypersthene (X pinkish-yellow, Z green). Grunerite, a blue-green hornblende, and magnetite are present in small amounts in these garnetiferous bands.

(iii) Hypersthenite (25367).—The most striking rock from the meta-jaspilite area to the south-west of Mt. Mackie is (25367) which consists almost entirely of crystals of hypersthene up to 4 cm. long. The hypersthene (X yellowish pink, Z green) ; (—) $2V = 57° \pm 3°$) contains poikiloblastic inclusions of quartz and magnetite up to $\frac{1}{2}$ mm. in diameter. Intergrown with the hypersthene, and sometimes containing inclusions of it, are small twinned crystals of grunerite. Associated with the grunerite crystals, occasional patches of a blue-green hornblende with very strong absorption are seen.

Both the grunerite and the hypersthene are altering along planes of fracture to radiating aggregates of a yellow fibrous amphibole, associated with which are granules of secondary magnetite, now altering to hematite. The orthorhombic habit of the amphibole shows it to be a ferroanthophyllite, although Miles (1947 (a), p. 139) determined a similar yellow fibrous alteration product (in a hypersthene-magnetite rock from Greenhills) as a cummingtonite-grunerite.

(iv) Cummingtonite-magnetite granulite (25576).—Fine grains of magnetite (to $\frac{1}{8}$ mm. in diameter) form a rudimentary banding in these otherwise poorly bedded rocks. The magnetite is set in a granular aggregate of pale green prisms of cummingtonite which show an attempt at a preferred orientation (Text fig. 4A). This rock-type is easily distinguished from the other meta-jaspilites by its pale green colour and soft soapy " feel," due to properties peculiar to the cummingtonite and its weathering products. The cummingtonite, which forms prisms up to 2 mm. in length, has the following properties : X colourless, Y pale olive, Z very pale green ; $Y > Z > X$; $Z \wedge c = 9° \pm 2°$; (+) $2V = 82° \pm 4°$. The mineral is not a true cummingtonite for one 110 cleavage shows a better development than the other and c lies 3° off the optic plane ; this mineral is triclinic.



Text Figure 4.

Cummingtonite-magnetite granulite.

A. "Normal" rock—a granoblastic aggregate of prisms of pale green cummingtonite (cleavage), altering in places to chlorite (irregular flakes). Magnetite (black), in small grains, is scattered throughout the rock.

B. 25388. Highly altered rock. Only a few relicts (showing cleavage) of the original cummingtonite crystals (outlines dotted) remain in a groundmass of talc and chlorite (irregular flakes) with primary and secondary magnetite.

A metajaspilite, from the Malkup Area, containing cummingtonite associated with a blue-green hornblende was described by Cole and Gloe (1940).

There is a marked variation in the degree of alteration of the cummingtonite. The type specimen shows a partial alteration to pale green chlorite. In (25578) and (30025) the chlorite is joined by a highly birefringent talc as a second decomposition product. (25388) consists almost entirely of colourless chlorite, talc and primary and secondary magnetite. In this specimen, alteration has proceeded almost to completion, only a few scattered, partially decomposed cores of cummingtonite crystals remain in the midst of a jumble of chlorite, talc and magnetite (text fig. 4).

A variant of this rock-type is found in (25369) where a pale green hornblende (X colourless, Y olive green, Z pale green) is associated with the cummingtonite, chlorite and magnetite.

(v) Grunerite metajaspilites.—Specimen (25397) shows the excellent sedimentary banding characteristic of the metajaspilites. It is divided into bands 4 mm. wide, containing two amphiboles, and 3 mm. wide bands of quartz. The amphiboles are grunerite and a blue-green hornblende with a very strong absorption. The nature of this hornblende, the intense colour of which is due to its high iron content, was discussed by Miles (1943, p. 36). He mentioned its occurrence in crystals which are in optical continuity with grunerite. In both this specimen (25397), and in (25440), crystals of grunerite contain patches of the hornblende in optical continuity with the grunerite. The

grunerite, which, in places, shows a brownish-black turbidity, due to alteration to (?) hematite, has the following properties :—$Z \wedge c = 16°$, (—) $2V = 84°$, $110 \wedge 1\bar{1}0 = 55\frac{1}{2}°$ The extinction angle is noticeably higher than that normally cited for grunerite (11°).

Specimen (25402) is a type midway between the grunerite metajaspilite and the cummingtonite metajaspilite. As in the cummingtonite metajaspilite, the original sedimentary banding is retained in bands of magnetite crystals, now altering to hematite and comprising 20 per cent. of the rock. The blue-green hornblende is abundant (15 per cent.) and occurs in bands associated with magnetite, chlorite, and hematite. Apart from occasional crystals of quartz (5 per cent.), the remainder consists of an equigranular aggregate of cummingtonite and grunerite. The overall texture is that of a fine-grained granulite, no grain exceeding $\frac{1}{2}$ mm. in diameter.

A totally different type of grunerite rock is illustrated by (30024). The closest parallel rock-type to (30024) is the hypersthenite (25367), which comes from the same large metajaspilite lens to the south-west of Mt. Mackie. The rock contained large crystals, 6 cm. or more long, of grunerite which is now altering to a mass of fibres of ferroanthophyllite. These fibres radiate from a series of parallel cracks, containing magnetite crystals, which apparently represent the original bedding. Only a few relicts of the original grains of grunerite remain. They have been bleached by weathering but can be distinguished by their inclined extinction and multiple twinning. Most of the rock is now an aggregate of yellow to colourless fibres of ferroanthophyllite. Here and there are seen flakes of yellow-brown biotite.

(vi) Grunerite-hypersthene metajaspilite (25440).—Alternating throughout this rock are two distinct types of bands each 1 cm. wide. One contains coarse crystals of black amphibole and quartz, the other consists mainly of silky-lustred fibres of a dark green amphibole arranged with their long axes at right angles to the banding. Within the latter bands are layers of magnetite crystals and fine grains of amphibole paralleling the main banding. Associated with the magnetite bands are grains of rutile and apatite.

On microscopic examination the fibrous layers are seen to be composed of a very fine aggregate of pale needles of grunerite ($X = Y$ colourless, Z very pale green). Occurring amongst the fibrous mass are bands of granular crystals of twinned grunerite, averaging $\frac{1}{2}$ mm. in diameter. Some of these crystals are in optical continuity with crystals of the blue-green hornblende. Near the margin of one of these fibrous areas, two large crystals, cored by blue-green hornblende, show irregular alteration to pale-coloured grunerite along their margins.

The intervening bands consist of quartzose granulite in which crystals attain 3 mm. in diameter. The main mineral developed in this band is a turbid amphibole with two well-developed, but unequally developed, cleavages. One cleavage is perfectly formed, its cleavage planes being very closely spaced, imparting to the mineral the appearance of diallage. Set about midway between the two cleavages is a plane of multiple twinning. This twinning is also visible on sections in which the cleavage does not show. The twinning and high birefringence of this amphibole point to grunerite, whereas the unequally developed cleavages and the positive optical character, as shown in some sections, indicates a triclinic " cummingtonite."

Associated with this mineral are crystals of the blue-green hornblende and a hypersthene (X yellow to colourless, Z green) which is notable for a

well-developed multiple twinning parallel to the optic plane. The grunerite, hypersthene and hornblende when in contact with grains of quartz, show alteration to fine needles of ferroanthophyllite as in the garnet-hypersthene metajaspilites.

3. Granites.

A large boss of homogeneous equigranular fine-grained granite outcrops in the central-western part of the area. Elsewhere the granite is found in dykes, ranging from 1 inch to 10 feet or more in width, traversing the gneiss and its associated quartz veins and pegmatite dykes. The granite is therefore younger than the pegmatites. The intrusive relationships of these rocks are seen in Plate III (b). The granites in the dykes and in the boss are grey coloured acid rocks in which biotite does not exceed 10 per cent. In some dykes the biotite content is so small that the rock might be called an aplite.

(a) *Microcline-oligoclase-biotite granite* (25551).

(25551) contains microcline, oligoclase, biotite and quartz in grains averaging ½ mm. in diameter. Microcline, which is the most abundant mineral, is in clear, unaltered grains, some of which contain small rounded inclusions of quartz. The oligoclase ($Ab_8\ An_2$) has a turbid appearance due to alteration to white, highly birefringent sericite. In some specimens well-developed flakes of muscovite, growing parallel to the cleavage of the oligoclase, have developed. The reason for this unusual alteration product of the oligoclase was discussed earlier. Reaction with neighbouring crystals of microcline has produced myrmekitic blebs of quartz in some crystals of oligoclase. Quartz and brown biotite, which is altering to a greenish chlorite, are the other constituents.

(b) *Porphyritic microcline granite.*

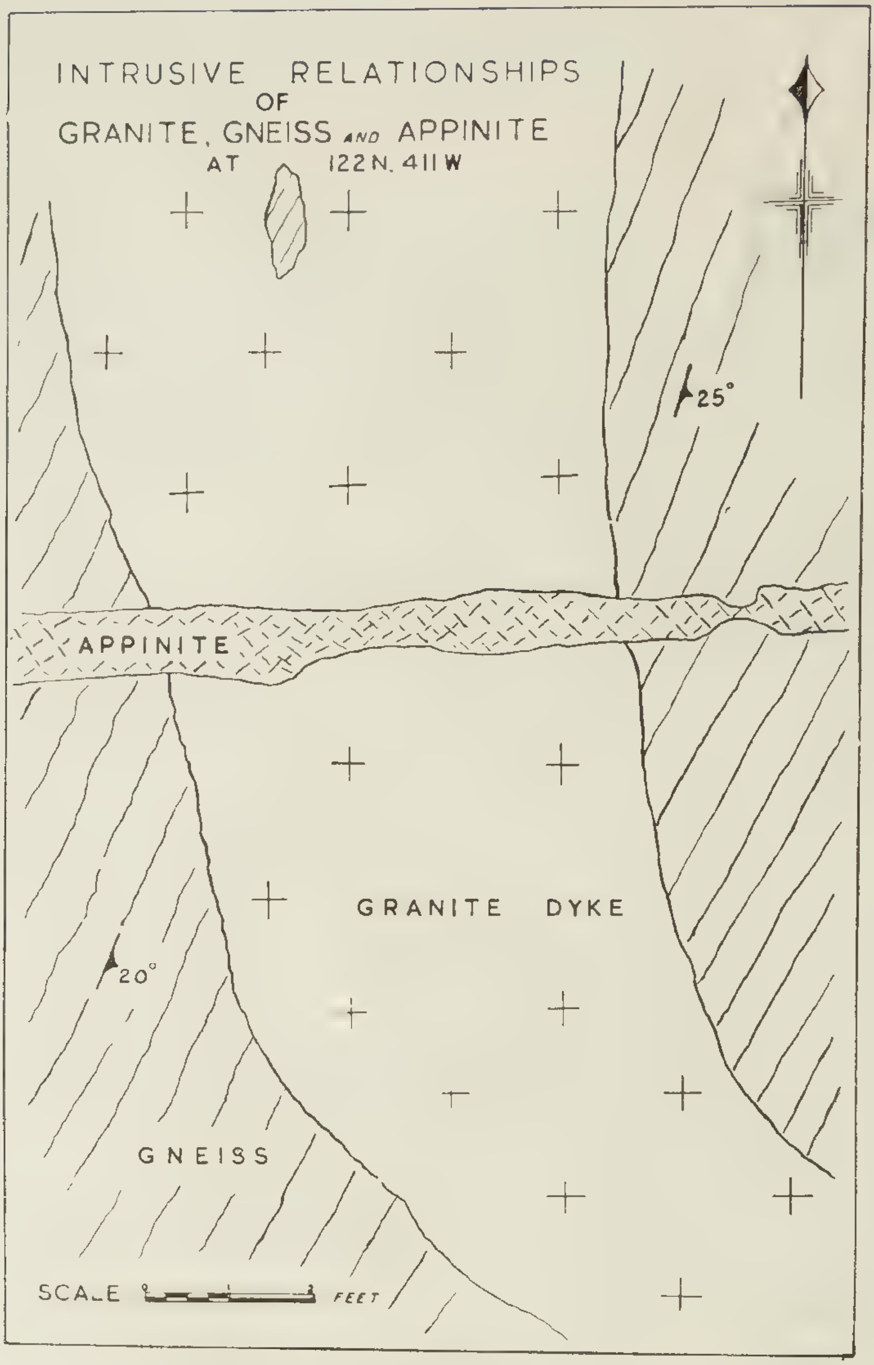
Numerous phenocrysts of microcline, all showing perfect or near-perfect crystal form, are characteristic of this medium-grained microcline-oligoclase-biotite-hornblende granite. It is similar to that found to the south of Clackline and described by McWhae (1948, p. 66).

Though not occurring within the area under review this rock has been noted three miles to the west of the metasedimentary bands, its contact being roughly parallel to the western border of the area.

(c) *Appinites.*

The appinites or hornblende granites are fine-grained, grey-coloured, intermediate rocks which occur as dykes or irregular shaped patches in the granite and gneiss. Two distinct rock-types, whose chemical compositions are probably indentical, fall into this group. The most common type contains microcline, hornblende, chlorite, oligoclase and sometimes quartz ; the other contains chloritised biotite, oligoclase and quartz. Although having the form of xenoliths in the gneiss, these occurrences are noted for their very sharp contacts. In some outcrops, notably one at the waterfall in Cobham Brook, the edges of the dykes are marked by partially resorbed oligoclase crystals identical with those in the surrounding gneiss.

At a small waterfall 122 chains north, and 411 chains west of datum, a narrow dyke of biotite-oligoclase appinite traverses both the gneiss and a granite dyke (text fig. 5). From this it would appear that the appinites are younger than both the gneiss and the fine-grained granite (the " younger granite ").



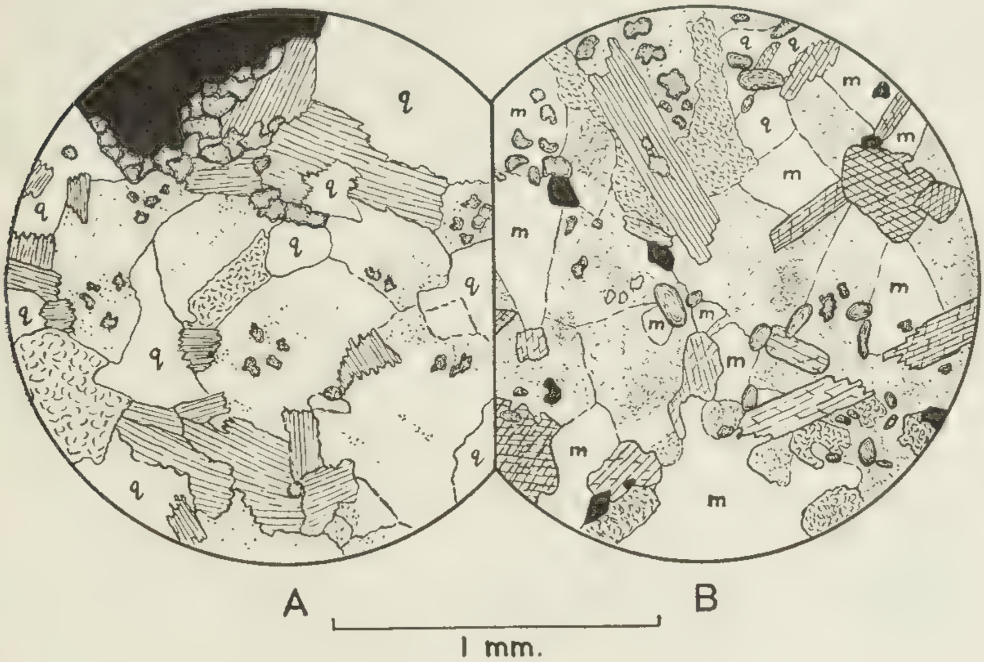
Text Figure 5.

Geological sketch map at 122 N. 411 W.

The occurrence of these hornblende granites in the Western Australian Pre-Cambrian has been known for some time, although their relationship to the other igneous rocks was obscure. One of the earliest records of this rock-type is found on a map of the Muresk area by Prof. E. de C. Clarke and Messrs. F. G. Forman and A. B. Adams (1927). Several bands of hornblende granite, paralleling the structure in the surrounding gneiss, are shown. Examination of a specimen (7262), from one of these bands showed it to be the hornblende-microcline appinite.

The biotite-oligoclase variety of appinite was noted, in the Toodyay area, by Prider (1944, pp. 112–3). The rocks are described as " irregular-shaped, elongated, darker-coloured, patches, in which the foliation approximates to

that in the surrounding gneiss." The sharp boundaries of these "xenoliths," with complete absence of any transitional zone, is characteristic of this rock-type.



Text Figure 6.

Appinites.

A. 25376. Biotite-oligoclase appinite. Clots of biotite flakes (with cleavage), now completely altered to chlorite, occur in a granoblastic aggregate of quartz (q) and oligoclase (partly saussuritised). Patches of chlorite (irregular flakes) are associated with the biotite. Occasional large crystals of pyrite (black) rimmed with granular epidote are found.

B. 30030. Microcline-hornblende--oligoclase appinite. Hornblende, in dark green prisms (imperfect cleavage), associated with chlorite, epidote (high relief, irregular grains) and sphene (high relief, rounded grains) is the main ferromagnesian. A crystal of chloritised biotite appears in the upper left of the field. The felspars are unaltered microcline (m) and saussuritised oligoclase. Quartz (q) and pyrite are present.

(i) Biotite-oligoclase appinite (25376).—This specimen, from the type-locality at (122N, 411W), contains oligoclase (40 per cent), chloritised biotite (30 per cent), quartz (20 per cent), with pyrite and epidote comprising the remainder. The thick books of completely chloritised biotite, from $\frac{3}{4}$ to 2 mm. in length, collect in basic clots, 3 mm. or more in diameter— a feature common to both varieties of appinite. Between these basic areas, an equigranular, equidimensional aggregate of quartz and slightly saussuritised and sericitised oligoclase occurs (text fig 6A). Large crystals of pyrite are sparsely scattered throughout the rock. Some of these are surrounded by a rim of granules of epidote. Elsewhere, epidote is associated with the clots of biotite and occurs as the product of saussuritisation of the oligoclase.

In mineral content this specimen resembles (25602) from the waterfall in Cobham Brook. (25602) is very fine-grained ($\frac{1}{16}$ to $\frac{1}{8}$ mm. in diameter) containing quartz, magnetite, oligoclase (Ab_{83} An_{17}) and a brown biotite (X yellow, Z deep brown). The biotite, which does not show alteration to chlorite, is in thin flakes $\frac{3}{4}$ mm. long. These have a decussate arrangement in the centre of the dyke, but, near the margins, become aligned parallel to the contacts of the dyke.

(ii) Hornblende-microcline-oligoclase appinite (30030).—About 30 feet from the type-locality of the biotite-oligoclase appinite, a dyke of hornblende appinite, several feet wide, occurs. Specimen (30030) was collected from this dyke. It contains 60 per cent of an equidimensional equigranular aggregate of clear, unaltered microcline and partly saussuritised and sericitised oligoclase. Myrmekitic reaction structures are occasionally found at the contact of these minerals. Prisms of a blue-green hornblende with strong absorption (X yellow-green, Y deep olive green, Z deep blue-green ; $Y>Z>X$) occur in groups throughout the rock. This hornblende has altered in places to irregular shaped aggregates of a deep green chlorite with yellow-green pleochroism and strong absorption. Occasional well-formed laths of chloritised biotite are present (Text fig. 6B). Associated with the ferromagnesians, and occasionally included in them, are rounded granules of sphene, irregular shaped grains of epidote and cubes of pyrite. Epidote is also an associate of the saussuritised oligoclase. Small grains of quartz are also present.

The hornblende appinites frequently contain relict crystals of felspar—residuals from the gneiss ; occasionally, patches of granitic material occur as xenoliths in the appinite. Throughout these rocks saussuritisation and epidotisation are common processes, one dyke (25574) containing visible clots of epidote.

(30031) is identical in composition with (30030). It contains microcline, quartz, saussuritised and sericitised oligoclase, blue-green hornblende and chloritised biotite with epidote, sphene, pyrite and apatite as accessories. It comes from the fine-grained granite boss in the central western part of the area, where the appinite occurs in irregular shaped, grey-coloured patches in the granite. Although their contact with the granite is sharp, these patches have the appearance of xenoliths rather than bodily injections. Along the banks of Heale Brook several exposures of granite show bands of appinite lying parallel to the strike of the adjacent metasediments. Some of the appinites may possibly represent recrystallised basic bands in an originally gneissic terrain. But whatever the origin of the irregular shaped patches in the granite, the dykes traversing both granite and gneiss must have a similar genesis.

(30031) also contains scattered yellow-brown blebs of quartz. These are composed of a coarse interlocking mosaic of quartz grains which are partially digested by the appinite ; crystals of biotite are prising the quartz crystals apart. Nearby the granite has partially absorbed a band of chrome-muscovite quartzite (120) N, 394 W.)

Table 1.

Chemical analysis of appinite (30030).

			Norm.	
SiO_2	53·02			
Al_2O_3	18·68		or	21·68
FeO	3·98		ab	30·39
Fe_2O_3	3·09		an	23·91
TiO_2	1·12			
MnO	·14		di	7·60
CaO	7·56		hy	6·05
MgO	3·09		ol	0·93
K_2O	3·68			
Na_2O	3·62		mg	4·41
H_2O—105°C.	·10		il	2·13
H_2O+105°C.	·97		ap	1·68
CO_2	*Nil*			
P_2O_5	·71		Classification II, 5, 3, 3 (4).	
	99·76			

Analyst.—W. H. Herdsman.

This slightly undersaturated rock shows chemical affinities with the dolerites and shoshonites of the shoshonase group in the C.I.P.W. classification.

4. Younger Basic Intrusives.

All the rocks described above are traversed by quartz dolerite dykes, injected into two sets of tension fractures trending N.N.W.–S.S.E. and E.N.E.–W.S.W. respectively. Minor dykes, in the centre of the area, have a N.W.–S.E. trend. The majority are relatively fine-grained, much-epidotised dolerites; others are coarse-grained acid gabbroidal dolerites ; a third intermediate variety contains phenocrystal laths of saussuritised plagioclase averaging 5 mm. x 1 mm.

(a) *Quartz dolerite* (24669).

This is a typical dolerite consisting of an ophitic intergrowth of partially saussuritised basic andesine with augite ((+) 2V = 45° approx.) and a green hornblende (X pale yellow, Y yellow-green, Z pale olive green ; $Z > Y > X$). Both the augite and hornblende show alteration to pale green fibrous uralite and greenish chlorite. Quartz and skeletal crystals of pyrite each comprise 5 per cent of the rock. Apatite is an accessory.

The large dyke, which has been traced over a length of more than 4 miles in the area mapped, belongs to this fine-grained type but it has been so saussuritised and epidotised that all the original plagioclase and ferromagnesians have been converted to a granular aggregate of epidote and chlorite. Quartz and pyrite are the only original minerals still intact.

(b) *Porphyritic dolerite* (24672).

Laths of highly saussuritised plagioclase, probably an andesine or labradorite form the greater part of this specimen. Scattered amongst these laths are large (2 mm. diameter) crystals of augite ((+) 2V = 45°) which show alteration to chlorite and sometimes to uralite. Associated with the augite are skeletal crystals of pyrite. Apatite is an accessory.

(c) *Quartz gabbro* (25395).

In the hand-specimen this rock has a coarse-grained gabbroidal appearance. The coarseness of grain is constant throughout the dyke, no diminution in grain size due to chilling at the margins being noted. Specimens from narrow dykes show the same coarse texture as those from dykes three or four times their width. This apparent paradox can be explained if this quartz gabbro magma was a hot, volatile end-phase injection ; temperature effects on crystal size would then be reduced to a minimum ; volatility would be the controlling factor. That this intrusion is such is indicated by the abundance of quartz and oligoclase and the presence of brown hornblende. The coarseness of texture of this rock-type is partly illusory, for, although the grain size is larger than that of the quartz dolerites, the segregation of the ferromagnesians into clots gives the rock an exaggerated coarse-grained appearance.

The rock consist of a sub-ophitic intergrowth of highly saussuritised oligoclase (Ab_{77} An_{23}), and quartz with several ferromagnesians. The primary ferromagnesians are a neutral coloured augite ((+) 2V = 45°) and a brown hornblende (X yellow-brown, Y brownish olive green, Z very dark brown ; $Z > Y > X$). Both the augite and hornblende are altering to uralite in crystalline and fibrous form. Crystals of augite have developed a " reaction rim " of chlorite in pleochroic (yellow-green) flakes. Epidote is a common alteration product. Skeletal crystals of pyrite and needles of apatite are the accessories.

5. Laterite.

The laterite, which is formed over granitic and gneissic rocks, is a strongly cemented pisolitic type. The pisolites contain a concentrically banded deep red-brown core with a paler exterior and are held together by a light yellow-brown ferruginous cement. Small angular quartz grains occur throughout the pisolites and matrix.

6. Quaternary Arkose. (30032)

A coarse-grained, gritty, arkosic sandstone occurs in a creek bed near (125 N, 339 W). It contains angular grains of quartz, 3 mm. in diameter, together with a partially kaolinised felspar and small angular chips of gneiss. Small, rounded, black grains of ferromagnesians are sparsely scattered throughout. The rock, which is, in places, well cemented and coherent, has a clay matrix no doubt derived from the kaolinised zone at the head of the stream.

Current bedding in this deposit indicates that it was probably laid down in a small, shallow, lake formed by some local interference with the water-table. This disturbance apparently affected a large area adjacent to Hamersley Siding, for the 1927 map of Muresk (Clarke, Forman, and Adams) shows a considerable deposit of an identical rock, specimen (7261), in the valley of Hughes Brook.

B. FLUORESCENCE TESTS.

Under the guidance of Mr. A. F. Wilson, the gneissic and granitic rocks were subjected to fluorescence tests with a short-wavelength ultra-violet lamp. The granitic suite near Hamersley is notably poor in accessory minerals, so, as expected, no important fluorescence of zircon or apatite was found. The felspars only were used in these tests.

It has been found (Wilson, 1950) that crystals of potash felspar, and sometimes plagioclases, when crystallised from an actual granite magma, or when formed by felspathisation, often exhibit a rose-pink fluorescence. If it can be established that the felspars of the original terrain do not fluoresce, then the process of felspathisation can be followed, by using the felspars as markers. The felspars of very fine-grained acid rocks, even if of magmatic origin, do not fluoresce.

The felspars of the gneiss from the central and eastern parts of the Hamersley Area showed no reaction to ultra-violet light. It is thus interpreted as being a recrystallisation *in situ* of a felspathic sediment—an arkose. The gneiss is not of magmatic origin, neither has it been subjected to felspathisation.

Near the margin of the massive granite, the gneiss contains crystals of fluorescent microcline. Here, apparently, the recrystallised arkose has received small additions of microcline from the adjacent granite mass. Specimen (25552) was one of those tested. It was found that occasional grains of microcline in the groundmass fluoresced, the microcline porphyroblasts being non-reactive. In this type of gneiss, therefore, although the rock has undergone felspathisation the materials of the porphyroblasts are native to the metasediment, not introduced.

Both the massive granite and its associated medium-grained dykes contain brightly fluorescing felspar, confirming their magmatic, or at least felspathised origin. The fine-grained granite dykes do not show fluorescing

felspars. All the specimens of appinite showed a bright pink fluorescence of their felspars. They are, therefore, interpreted as of magmatic origin, probably related to the granites.

C. PETROGENESIS.

1. Gneisses.

This hybrid complex contains a uniformly-banded medium-grained type, a coarse-grained porphyroblastic type, and a fine-grained well-banded type showing all the characteristics of a metasedimentary gneiss.

Prider (1944, p. 107) considers that the gneisses of the Toodyay Area are magmatic intrusions. He bases this concept on (i) the quartz grains lack preferred orientation and show no signs of strain, (ii) the gneiss contains xenoliths of metasediments and (iii) occasional discordant contacts are seen between the gneiss and the quartzite.

McWhae (1948, p. 65) suggests that the gneiss in the Lawnswood Area was introduced as " a highly viscous magma during the period of diastrophism." However, he found a hybrid granitic gneiss which he considers to be the result of granitisation of the basic lenses in the gneiss.

The gneiss at Hamersley is thought to be, not a magmatic intrusion, nor, in most places, a product of felspathisation, but a recrystallisation of an arkosic sediment under conditions of regional metamorphism. It seems very improbable that such a delicate structure as that shown on Plate I, could have withstood any degree of mobilisation in the gneiss, much less a bodily injection of a viscous magma without suffering severe dislocation or being totally destroyed.

Where strike and dip readings can be obtained, the foliation in the gneiss closely parallels the contortions of the metasedimentary bands thus emphasising their conformable relationship.

The presence of graphite in the gneiss at (37N, 270W) points to a sedimentary origin and indicates the probability that organic life existed in the seas in which these rocks were deposited. The fluorescence tests also indicate a sedimentary origin.

The high percentage of microcline and the pronounced sericitisation of the oligoclase in most specimens indicates that the parent rock was probably over-saturated with potash, probably a potassic arkose. The presence of the low temperature ($<$ 600°C) felspar, microcline, also indicates that the gneiss is a recrystallisation, *in situ*, of arkose, rather than a magmatic injection. Fluorescent tests show that the large microcline porphyroblasts in (25552) were not introduced by felspathisation but were developed from the original sediment because of its high potash content.

As noted by Ramberg (1949), the minerals developed in the pegmatites—microcline, oligoclase, biotite, and quartz—are identical with those in the surrounding gneiss. These minerals are characteristic of a relatively low temperature of formation. Hence the pegmatites do not necessarily represent minerals deposited from hot volatile magmatic fluids ; rather they may

represent zones in the gneiss where pressure-temperature-composition conditions were such that ionic diffusion could take place rapidly, thus enabling large crystals to form. The pegmatites are, therefore, interpreted as local variants in the gneiss and not bodily injections into it.

Near the edge of the granite mass in the west of the area the gneiss shows partial felspathisation, apparently caused by emanations from the granite. From the structure section (Plate I) it appears that, during its emplacement, the granite assimilated, rather than forced aside, the metasediments—this is evidenced by a quartzite xenolith in the granite mass. The granite may thus have been emplaced by the " soaking up " of the pre-existing gneiss and metasediments by the emanations from the west, rather than bodily injection of a plutonic magma. The granite may this be interpreted, in part at least, as a mobilisation of the pre-existing terrain. This mobilised phase was " injected " into the gneiss in the form of dykes which occur throughout the area, some being noted as far east as Mt. Mackie.

Associated with the granitic rocks are appinite dykes, the felspars of which show a pink fluorescence. Thus they may be interpreted as magmatic rocks, or at least as mobilised rocks, probably closely related to the massive granite. The chemical analysis of one of these appinites shows a similarity to analyses of rocks of a doleritic nature. Their dyke-like occurrence indicates that the appinites may be an associate of the quartz dolerite suite. However the appinites are undersaturated rocks whereas the dolerites are saturated. The irregularly-shaped patches of appinite in the massive granite to the west of the area possibly formed either from basic emanations which replaced the granite or by recrystallisation of basic lenses in the granite. Recrystallisation of basic lenses in an originally gneissic terrain seems an adequate explanation of the xenolithic bodies in the massive granite but it is inadequate to explain the " intrusive " dykes. Probably both the " xenoliths " and the " dykes " could be explained as the products of preferred replacement of country rock by basic emanations. Too little is known of the chemical compositions, modes of occurrence, and regional distribution, of the two types of appinite to make a definite statement of their origin at this juncture.

2. Quartzites and associated metasediments.

The quartzites, mica schists, cordierite-anthophyllite rocks, metajaspilites, etc., may now be considered as original lenses of differing facies in a basin of thick predominantly arkosic sedimentation. In such thick arkosic formations it is usual to find scattered lenses of such varied rocks as limestones, cherts and sandstones disturbing the uniformity of the main rock-type.

(a) *Hornblende granulites.*

The lenses of hornblende granulites are generally found near the main quartzite bands but are by no means abundant. As evidenced by their basic plagioclases and high percentage of hornblende, they are rich in calcium and probably are metamorphosed impure limestones, although Prider (1944, p. 121) considers them to be meta-basic igneous rocks.

(b) *Cordierite-anthophyllite rocks.*

With admixtures of clayey materials, the original arkose developed lenses of varying basicity. During metamorphism these were transformed into schistose and basic lenses, depending on the nature of their clay content. Thus the basic clay lenses gave rise to the garnet-biotite-sillimanite-cordierite-anthophyllite rocks. The sedimentary origin of these rocks is shown by their

division, by no means perfect, into quartzose and cordierite-rich bands. The variations in the rock-type reflect variations in the original sediments ; the more basic the original clay, the richer the resultant rock in cordierite, biotite and garnet. Thus (25168) contained so little basic clay that garnet did not form, and only thin bands of cordierite, sillimanite and biotite have formed in an otherwise normal oligoclase gneiss. This rock thus shows an intermediary development between the oligoclase gneisses and the cordierite-anthophyllite lenses.

(c) *Garnet-sillimanite schists.*

Associated with the main quartzite bands are sillimanite-muscovite and garnet-muscovite schists. Occasional lenses of schists also occur in the gneiss. The maximum development of sillimanite is found in ares of greatest deformation in the fold—at (80N., 340W.) (*see* text fig. 10) and at Mt. Mackie. Along the western limb of the fold, where a directed pressure is attained by the sliding of beds one over the other, a kyanite-anthophyllite-muscovite schist formed from the original pelitic sediments.

(d) *Quartzites.*

The quartzites show marked variations in mineral content. Lenses that were initially very pure sandstones have recrystallised as interlocking mosaics of large quartz crystals. These sandstones occasionally carried a few grains of microcline derived from the neighbouring arkosic facies of sedimentation. On metamorphism these grains remained as small ($\frac{1}{2}$ mm.) rounded crystals in the quartzite mosaic.

Minor quantities of aluminous material in the original sediment now appear in the quartzites as inclusions of sillimanite within the quarsz crystalls. As the clay content of the sediment increased, with admixtures of basic material, the resultant metamorphic derivative tends towards the garnet-sillimanite quartzite group. The garnet-sillimanite layers represent former clay bands in the rock. With a further increase in clay content the resultant rocks become garnet-sillimanite schists. The garnet-sillimanite-quartz schists are the main schistose rock-types found at Mt. Mackie (*see* text fig. 9).

As a result of metamorphism clayey sandstones, containing a little chromic oxide, have changed into quartzites containing sillimanite and the green chrome muscovite so characteristic of the quartzites of the Jimperding Series.

The quartzites have recrystallised as coarse-grained granoblastic rocks in which the individual crystals are firmly intergrown. However, in an area where the metamorphic processes were accompanied by large-scale molecular rearrangement, as evidenced by the coarse grain size developed in the gneiss, it does not seem necessary to postulate high temperature recrystallisation to explain their coarseness of grain. Rather, moderate temperatures aided by free and rapid molecular interchange between adjoining crystals, would account for both the large grain size and the plastic flowage of the quartz grains. However, sillimanite is present in these rocks and this indicates that these rocks have been subjected to high grade regional metamorphism.

(e) *Metajaspilites.*

The final important group of the metasediments is the metajaspilites. These range from magnetite quartzites to pure amphibole rocks.

The magnetite quartzites are well banded rocks which, from their close association with the massive quartzites, probably represent metamorphosed ferruginous sandstones.

The garnet-hypersthene-magnetite-quartz granulites, with their fine banding and intricate slump structures, represent ferruginous cherts which received varying additions of basic clays and subsequently suffered metamorphism. Here we have an enigma ; hypersthene, a characteristically " dry " mineral, is found in metajaspilites which are associated with gneisses and schists containing " wet " minerals—biotite, chlorite and muscovite. However, in basic metamorphic rocks containing free quartz, hypersthene is the stable ferromagnesian. Any water present in the original chert would be absorbed during metamorphism, by the formation of grunerite or, in some instances, of ferroanthophyllite.

In the complex metajaspilite lens to the south-west of Mt. Mackie, several coarse-grained rocks occur ; (25367) and (30024) contain large crystals of hypersthene and grunerite respectively. These rocks probably represent " dry " and " wet " portions of a ferruginous chert in which the silica was just sufficient to satisfy the other oxides. The small quantity of water in the hypersthenite was taken up in the form of grunerite. The ferroanthophyllite in both rocks represents post-metamorphic decomposition.

Variations in the composition of the original sediments are reflected in the marked diversity of minerals developed during metamorphism. Slight variations in chemical composition produce hypersthene-grunerite, grunerite-hornblende, grunerite-cummingtonite or pure cummingtonite rocks. The latter are particularly unstable and rapidly alter to an aggregate of talc and chlorite.

The metajaspilites are considered, by some geologists, to be metamorphosed sideritic and greenalitic cherts (Miles, 1947 (a)). The accepted origin of such rocks involves slow deposition in epi-continental basins, in which mechanical sediments are rare. Such basins are found at the margins of almost peneplaned land-masses. One would not expect to find these slowly accumulating deposits in a basin of rapid sedimentation where the predominant deposit was arkose—the product of rapid mechanical weathering of a youthful continent.

After prolonged study of the Soft Iron Ores (an oxidised form of the metamorphosed iron formation) of the Lake Superior Region, Tyler (1949, p. 1107) has concluded that not all the metamorphosed iron formations were originally rich in iron. He considers that they originally consisted of ferruginous cherts or sideritic cherts, in which the iron content was not very high, but was, nevertheless, higher than that of the surrounding sediments. On metamorphism, iron-rich solutions or emanations circulated through the rocks. The iron-bearing cherts were the loci for additional deposition of iron resulting in the formation of iron silicate minerals (grunerite, stilpnomelane and minnesotaite). The emanations enriched the cherts in iron content. Slightly ferruginous cherts, which do not require such specialised conditions of deposition as do the iron-rich types, may be so enriched in iron by emanations during metamorphism, that they become iron ores.

Miles (1947 (b)), came to a similar conclusion regarding the Western Australian metajaspilites. He cites evidence of jaspilites, within a zone of granitisation, being leached to a white cherty quartzite, whilst the meta-

jaspilites outside the granitised zone, were enriched in iron silicates and magnetite. With this evidence before us, it is possible that the metajaspilites at Hamersley were not necessarily very rich in iron when originally deposited. In the ionic reshuffling which accompanied the metamorphism and partial felspathisation of the gneiss, the jaspilite bands acted as loci for considerable accumulations of iron, magnesium and other elements. Variations in the composition of these ferromagnesian emanations from the gneiss are, in part, considered to be responsible for the varied types of metajaspilites in the area.

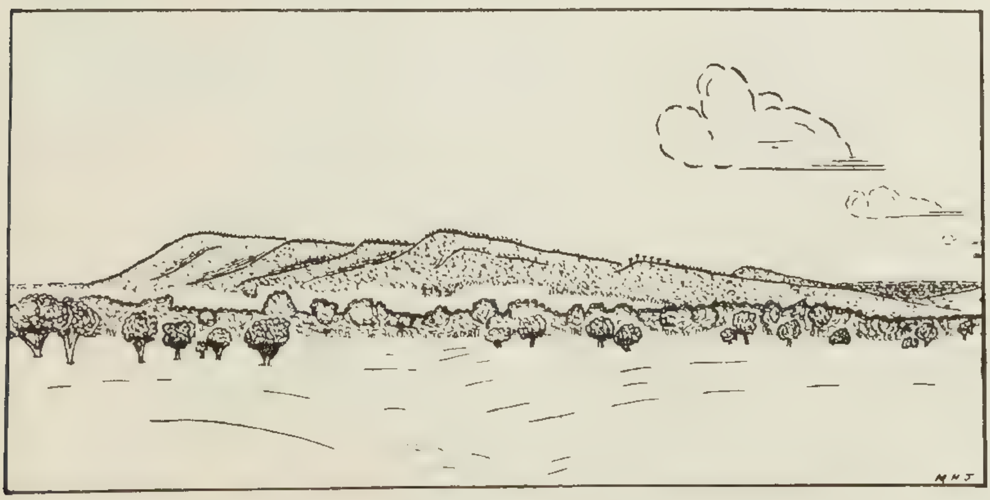
3. Quartz dolerites.

The latest intrusions are the quartz dolerites. The genesis of these rocks was discussed jointly with their petrography.

V. GEOLOGICAL STRUCTURE.

Major Structures.

The major structure in the area is a box-fold type of anticline whose axis strikes N.N.W.-S.S.E. ; it is overturned towards the west. When the fold developed, the rocks were so plastic that mica flakes and quartz grains within the quartzite bands recrystallised with their long axes parallel to the axial line of the fold ; the axial line, the *b*-tectonic axis, is the intermediate direction of stress in the fold. Thus, on the bedding planes of the quartzites is a pronounced lineation, which is caused by the parallelism of the mica flakes and quartz grains (Plate III. (a)). The pitch of the lineation indicates the pitch of the axial line of the main fold.



Text Figure 7.

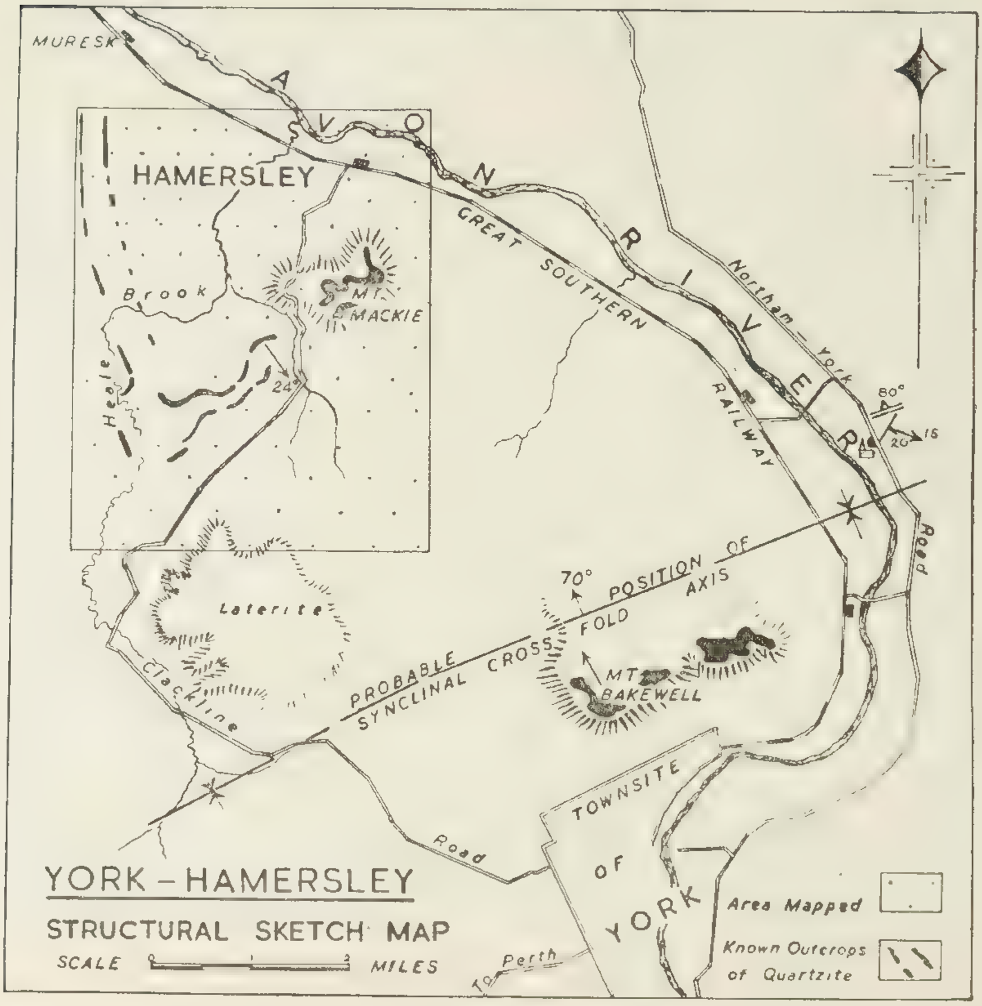
Mt. Bakewell, near York, from the north-east.

The crests of the hills are composed of quartzite which dips at approximately 10° to the north-west towards Mt. Mackie. At the foot of the distant escarpment lies the town of York. The line of trees in the middle distance marks the bed of the Avon River which flows from the left to right.

(Drawn from a photograph by the author.)

The main N.N.W.-S.S.E. folding is buckled by a series of E.N.E.-W.S.W. crossfolds. Consequently the *b*-lineation in the Hamersley Area now pitches to the south-east at an average of 24°. This places the area on the south limb of an anticlinal crossfold with the anticlinal crossfold axis to the north

and the synclinal crossfold axis to the south. Mt. Bakewell, near the township of York, and 5 miles to the south of Hamersley, is capped by quartzite which pitches approximately 10° north-west towards Mt. Mackie (text fig. 7). In a quarry near a small Church at Wilberforce, 6 miles from York on the Northam-York Road, the pitch of the lineation in the quartzites is 16° to the south-east (text fig. 8). The synclinal crossfold axis is apparently situated between the church and Mt. Bakewell.



Text Figure 8.

Structural sketch-map, Hamersley to York.

Showing the approximate position of the crossfold axis between Mt. Mackie and Mt. Bakewell.

The crossfolding, while probably part of the same orogeny, occurred later than the main folding, for, whilst plastic structures such as drag folds and *b*-lineations are associated with the major fold, the crossfold has only a fracture cleavage associated with it. The fracture cleavage, where measured at Hamersley and at the church, has an average strike of 71° and dip of 70° to the N.N.W. These might represent the strike and dip of the axial plane of the crossfold.

Structure and Facies Change.

The structure section (Plate I.) shows two thin beds of quartzite which dip steeply in the western part of the area, are relatively flatlying in the centre, and coalesce in a great mass of quartzite to the east of Mt. Mackie. Two interpretations may be made :—

1. The beds may be the same bed on opposite limbs of a very tight isoclinal fold with its apex at Mt. Mackie.
2. The structure may be considered as a simple box-fold type anticline in which the apparent isoclinal fold may be explained as a facies change.

The former was discarded because such a fold would require at least two orogenies for its formation and because any attempt at a structural interpretation of the area is hampered by the dearth of primary sedimentary structures in the well-bedded quartzites which would determine the order of super-position. The quartzites are so pure that the few outcrops, on which current bedding could be faintly discerned, proved to be undecipherable. Lacking confirmation, by means of primary structures, hypotheses implying overturning, *e.g.*, the isoclinal fold theory, cannot be proven other than by the doubtful criterion of dragfolding.

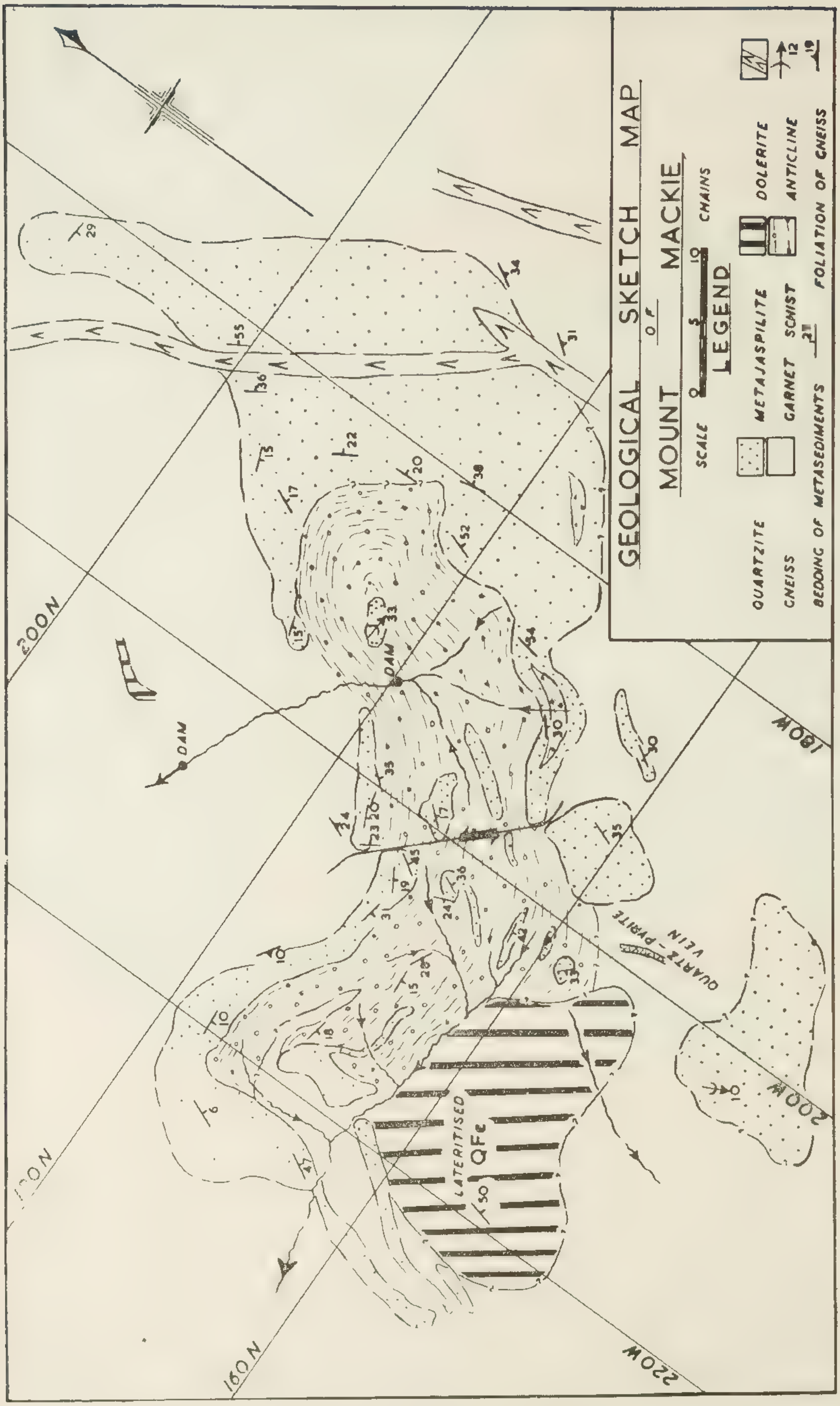
The structure, then, is considered to be a simple box-fold type anticline, the western limb of which, as delineated by the two bands of quartzites, is overturned in the western part of the area where it now dips at approximately 70° to the east. The eastern limb has not been located.

As noted in the section above dealing with petrogenesis, the arkose formation contained numerous lenses of varied composition. It may thus be interpreted as a shallow-water deposit with very rapid changes in facies. The succession was probably as follows :—

1. The deposition of a great thickness of arkose.
2. The formation of a widespread discontinuous sheet of sandstone, together with shales and cherts.
3. Further deposition of arkose, except in the area where Mt. Mackie is now situated. In this region a thick layer of sandstone, associated with clays and cherts, was deposited.
4. The deposition of another sandstone layer, cherts, etc.
5. Finally, the uninterrupted deposition of arkose continued.

The reason for the deposition of the sandstone in two semi-continuous bands is difficult to explain. They may represent a transgression and regression of a beachline, or the meandering of the sandy bed of a river across an arkosic delta formation.

Thus, owing to a facies change, the quartzite marker beds, which delineate the west limb and the crest of the box-fold, die out at Mt. Mackie. Because of this loss of marker beds, very careful mapping of the planar and linear structures in the gneiss will be necessary to determine the position of the east limb of the fold. The quartzite at Mt. Bakewell may represent a continuation of the same sandstone facies and the mapping of that area will probably assist in the determination of the position of the east limb.



Text Figure 9.

Geological sketch-map of Mount Mackie.

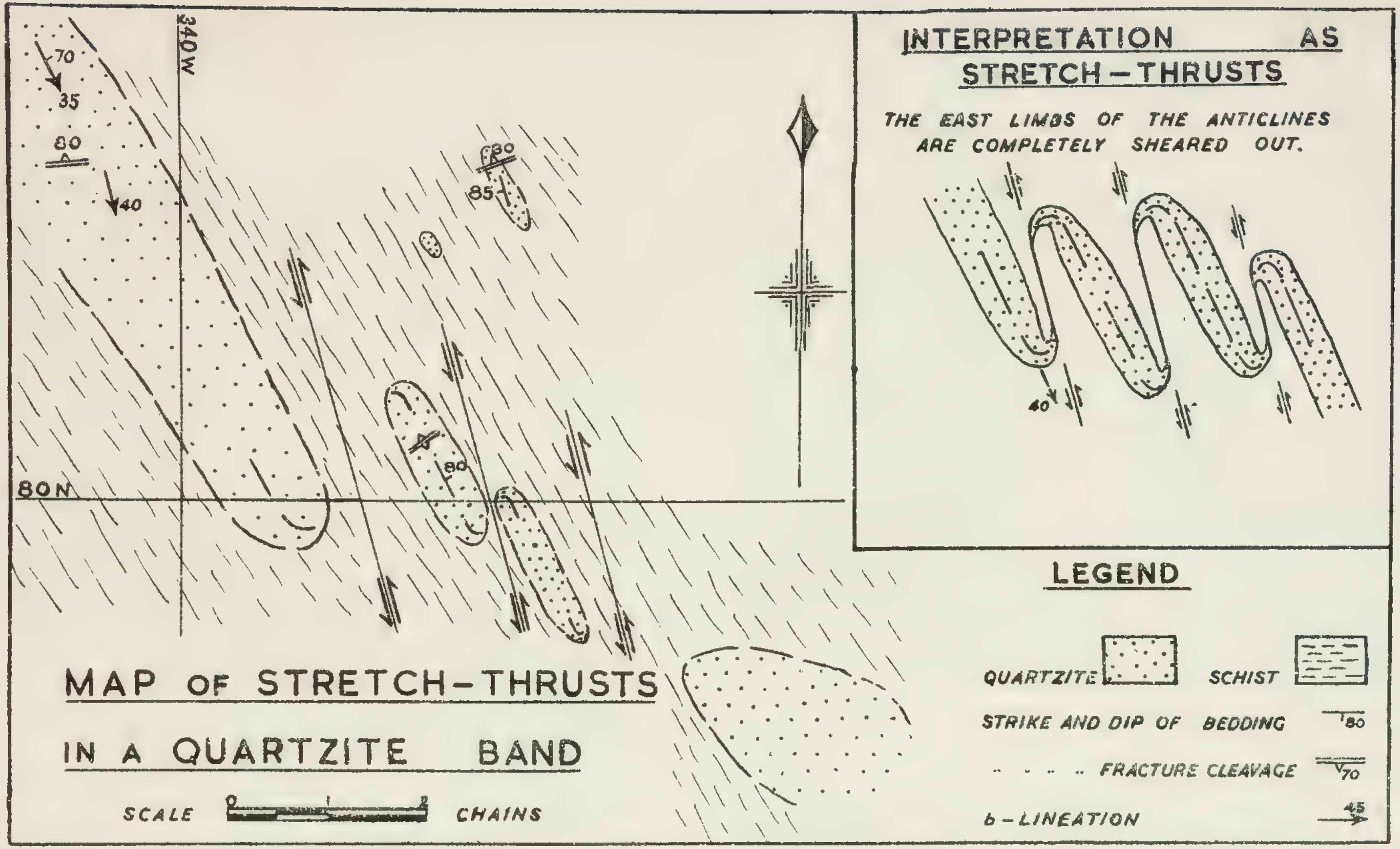


Figure 10.

En echelon lenses of quartzite and their interpretations as stretch-thrusts.

Mt. Mackie (Text fig. 9).

The alternating bands of quartzite and garnet-sillimanite schist at Mt. Mackie provide the best outcrops in the Hamersley Siding Area. There, the quartzites stand up as resistant ridges, approximately 100 ft. above steep valleys carved out of the weaker schists. Among the blocky quartzite outcrops are numerous exposures of bedding planes from which strike and dip readings were obtained. These showed minor contortions superimposed on the major synclines and anticlines developed there. The contortions were very pronounced in the vicinity of a small fault or stretch-thrust which is shown in the centre of text fig. 9. In the western part of Mt. Mackie, a large amphitheatre of quartzite has developed around the exposed margin of a south-pitching syncline.

Stretch-thrusts.

At the western corner of the boxfold, which outcrops at (80 N, 340 W), the lower quartzite is extremely contorted. It outcrops in a series of *en echelon* lenses in each of which the strike of the bedding parallels the length of the lens (text fig. 10). At first sight the quartzite appears to have been broken into lenses by a series of thrust-faults. However, the deformation occurred when the rocks were in a plastic, not a brittle, state and therefore folding, rather than faulting, is the more likely mode of origin of their present structure. A closer examination revealed that the strike curved round at the end of each lens. Thus the lenses may be interpreted as the alternate limbs of a closely packed series of folds from each of which one limb has been completely sheared out. These are the "stretch-thrusts" mentioned by Conolly (1946, pp. 166–7).

Shear zones.

Lenses of "finely crushed quartzites"—silicified shear zones—occur in lines traversing the area. Near (80 N, 360 W), a bedded quartzite is deflected by one of these shear zones, which are probably caused by re-adjustments of the rock mass after the main spasm of folding had passed, but before the rocks had lost their plasticity. To the south of Mt. Mackie, several lenses of quartzite have lunate ends, indicating that they were also involved in re-adjustments while still in a semi-plastic state.

VI. CONCLUSIONS.

The Hamersley Area is composed of a series of Pre-Cambrian metasedimentary rocks—quartzites, mica schista and gneisses—similar to those of the Jimperding Series of the country near Toodyay. They have been isoclinally folded and subjected to high grade regional metamorphism as have the Toodyay rocks ; but more fieldwork is necessary in the intervening country before detailed correlation may be effected with the previously described Jimperding Series.

The most contentious problem in connection with these rocks is the origin of the gneisses—these have previously been considered to be of igneous origin, but in the Hamersley Area various factors point to a metasedimentary origin for the major part of them : (1) fluorescence tests indicate that felspathisation (or the effects of magmatism) occur only near the granite mass to the west, (ii) wherever observed, the gneiss is conformable with the quartzites

and schists, and (iii) thin beds such as the quartzites could not preserve continuity were they involved in a large-scale magmatic intrusion such as that required to explain all the gneiss as a consolidated magma. If this conclusion be valid, the various quartzite, schist, and metajaspilite lenses in the gneiss must be explained as the metamorphic equivalents of quartzose, pelitic, and cherty facies in an arkose, instead of lenses of original country rock which have escaped granitisation or complete assimilation by a magma.

The granite to the west, which has apparently assimilated the country rock during its emplacement, displays intrusive relationships towards the older rocks—under the influence of "emanations," probably with admixtures of actual granite magma, a part of the pre-existing rocks was converted into a mobile granite mass which intruded the gneisses, quartzites and schists. The appinites are apparently related to this younger granite but their two distinct modes of occurrence are puzzling. Until detailed work is undertaken on other exposures of these rocks, such as those near Mt. Bakewell or at Muresk, any attempts at assigning an origin to them must be largely guesswork.

The quartz-dolerites and laterite are normal types, discussion of which has been presented in many previous papers on the Geology of parts of Western Australia.

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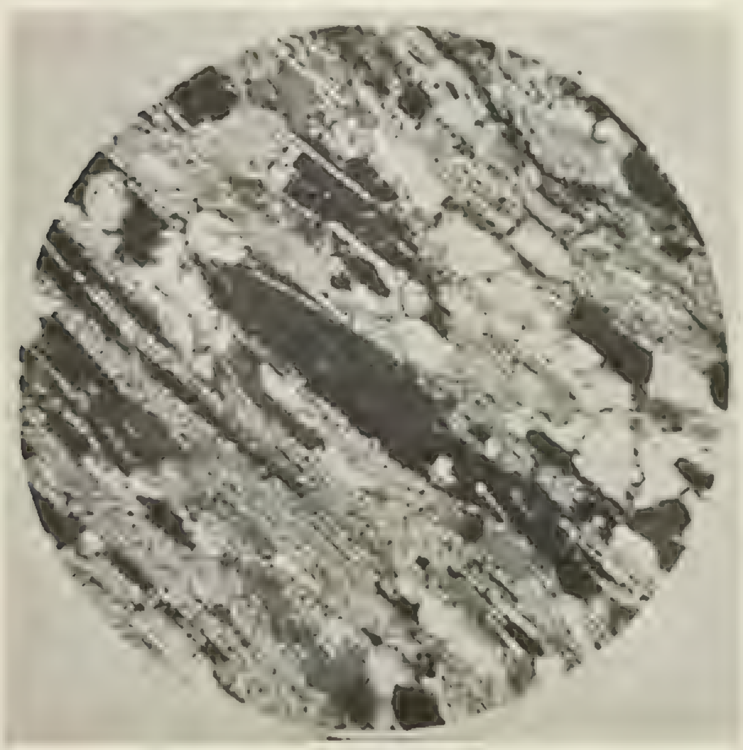
SECTION A–B

NATURAL SCALE

Plate II.

a. Crushed quartzite (24651) showing a large grain of quartz with marked undulose extinction which is being transformed into a fine, granular mass of quartz at its edges. (Crossed nicols, x 10). (H. J. Smith, Photo.)



b. Chrome-muscovite quartzite (25379) showing the intense deformation of the quartz grains. They are drawn out into long thing stringers, between which is developed a fine-grained aggregate of greenish chrome-muscovite. Needles of sillimanite can be seen in some quartz grains. (Crossed nicols, x 40.) (H. J. Smith, Photo.)

Plate III.

a. b-lineations in quartzite. The surface of the outcrop facing the observer is a bedding surface on the overturned west limb of the main fold. It dips away from the observer at 80 deg. The clinometer parallels the b-lineations on the bedding surface which here pitch 23 deg. to the south (photo. looking east). The hammer handle runs parallel to the marked fracture cleavage caused by the synclinal crossfold, the axis of which lies to the south.

(J. Lorimer, Photo.)

b. Intrusive relationships of granite and pegmatite. The gneiss, whose banding parallels the bubble arm of the clinometer, is traversed by two fine-grained pegmatite dykes. A later granite was injected along one of these dykes, and forced the other dyke aside. Thin quartz veins are the final injections.

(A. D. Hosking, Photo.)

Plate III.

a.

b.

5.—THE GEOLOGY OF THE WATTLE FLAT AREA, CHITTERING VALLEY, W.A.

by

J. K. GEARY, B.Sc., F.G.S.

Communicated by Professor R. T. Prider, 13th June, 1950.

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ABSTRACT.

The area described lies in the northern part of the Chittering Valley and consists of an isoclinally folded series of metamorphic rocks of early Archaeozoic age, intruded by uralitized dolerites. These Pre-Cambrian rocks are overlain by later formations of ferruginous sandstone, laterite and yellow sand. The earlier sections of the paper are confined mainly to a factual account of the geology of the area and the petrography of the various rock types. In the discussion the mode of origin of the different rocks is considered. Regional metamorphism of sediments and granitization are thought to be the agents responsible for the formation of the metamorphic complex. It is likely that the ferruginous sandstone is part of the Bullsbrook Series of lacustrine sediments. The origin of the later yellow sand is not known with certainty.

I. INTRODUCTION.

The area examined is about $3\frac{1}{2}$ miles square and lies in the upper reaches of the Chittering Valley. Its extreme south-western corner is situated a mile to the east of Cullala Siding, which is 62 miles north of Perth along the Midland Railway. It is accessible by road both through Bindoon and Mooliabeenee.

A few mixed farms are found in the broad mature valleys of the Brockman River (also known as the Chittering Brook) and its tributaries.

Geologically, the area consists of a series of isoclinally folded schists and gneisses overlain to the west by ferruginous sandstone and still later yellow sand. Simpson (1926) has described the occurrence of staurolite and kyanite within the area examined. The metamorphic rocks of Wattle Flat are the northerly extension of a similar complex occurring at Lower Chittering for which Miles (1938) proposed the name "Chittering Series." These rocks have also been described from Gillingarra, some 20 miles to the north of Wattle Flat, by Ivanac (unpublished MS.).

The Chittering Series is known to extend through Bullsbrook but a little further to the south it gives place to the Darling Range granites and gneisses. A rather similar series of metamorphic rocks, the "Jimperding Series" has been described at Malkup (Cole and Gloe, 1940), Jimperding (Prider, 1934), Toodyay (Prider, 1944) and Lawnswood (McWhae, 1948). The exact relation of the Jimperding to the Chittering Series is not known, since the country between Malkup and Lower Chittering has never been geologically examined, but both are thought to belong to one and the same complex, the Jimperding Series being a sandy facies and the Chittering Series a clayey facies.

The geological mapping of the area was carried out mainly by chain and compass traverses, which were tied to surveyed roads and fences plotted from the data of the Lands and Surveys Department and the Titles Office. The origin of the co-ordinate system used in this paper to describe the location of places mentioned is the south-west corner of Location 1166. A small section of the area was mapped by plane table and telescopic alidade. Most of the streams, laterite mesas and contacts of yellow sand and Pre-Cambrian rocks were mapped from aerial photographs, subject to frequent ground checking.

The earlier sections of this paper are confined, as far as possible, to a factual description of the geology of the area and the petrography of the different rock types. The conclusions, hypotheses and discussion arising from these facts are dealt with in the discussion section. Although this procedure involves a certain amount of reiteration, it is felt that this is warranted by the desirability of separating fact from theory.

The numbers mentioned in the petrographic descriptions refer to catalogued specimens in the collection of the Geology Department, University of W.A.

II. PHYSIOGRAPHY.

The main physiographic feature of the area is the Brockman River, a stream which flows to the south through a mature valley. Although its main directional tendency is from north to south, this stream makes an almost right-angled bend in the central part of the area and flows in an easterly direction for about a mile. However, if one consults a map showing the entire course of the Brockman River from its source just to the north of Wattle Flat to the point where it joins the Swan River at Upper Swan, it will be seen that its flow is almost directly north-south, and is evidently controlled by the regional strike of the Chittering Series (Jutson, 1934).

Except in the rainy season the flow of the Brockman River in this area is very sluggish and in the dry months of the year it ceases altogether. It is fed by a number of small tributaries which head near the high laterite

mesas and flow only in the winter. The course of the main stream where it flows through the Pre-Cambrian rocks is characterised by a fairly broad alluvial plain, but where it flows through the later sand formation, this plain practically disappears and the watercourse becomes a dense ti-tree swamp. The courses of some of the minor streams through the alluvial plain are extremely meandering.

In addition to the tributaries feeding the Brockman River there exist in the yellow sand formation a few broad shallow water-courses, again heading in the laterite mesas. These are dry in all but exceptionally rainy periods.

The topography is usually hilly in the areas of Pre-Cambrian rocks and gently undulating in the yellow sand formation. A noteworthy topographic feature is that where there is alternation of bands of metasediments of different resistance to weathering (gneiss and mica schist, for example) there are a number of prominent sharp-crested ridges running parallel to the strike of the rocks. In the eastern part of the area however, where the rocks are more uniform in character, these parallel ridges are not present although the topography is hilly. The steep slopes of the majority of the hills, especially the parallel ridges, are characterised by abundant talus.

The intrusive dolerite dykes may be marked by small ridges or small depressions according to the resistance to weathering of the rocks they intrude.

III. THE FIELD RELATIONS OF THE ROCKS.

As previously mentioned the area consists essentially of a Pre-Cambrian metamorphic and igneous complex, unconformably overlain by ferruginous sandstone and a still later sand formation.

The metamorphics are a series of gneisses of extremely variable character, micaceous schists often containing kyanite and more rarely staurolite and garnet, hornblende schists and minor amounts of quartzite. Although large bands of quartzite are rare, small bands and lenses a few inches in width are frequent in the schists and gneisses. In addition to these original quartz lenses, later intrusive vein quartz is very abundant. Usually this is concordant with the country rock, but it is quite often seen transgressing it, following lines of weakness such as joints. Sometimes this quartz is found to contain well developed kyanite crystals.

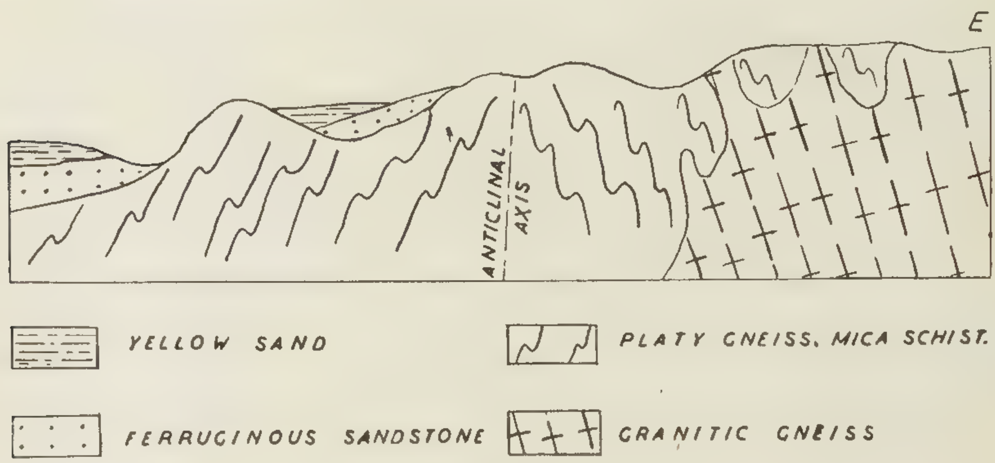
Probably belonging to the same period of intrusion as the quartz veins, but much less abundant, are a few veins and dykes of pegmatite. The eastern part of the metamorphic complex consists of a gneiss, the coarse grain and uniform composition of which contrasts strongly with the finer grained varieties of gneiss in the west. The coarse-grained gneiss is not intercalated with mica schist, but does contain numerous basic lenses. The strike and dip of the rocks of the metamorphic complex is fairly constant, the strike being essentially north-south and the dip practically vertical.

The metamorphic complex is intruded by later dolerite dykes and epidote veinlets that are apparently associated with them. A reconnaissance survey made to a distance of about a mile to the east of the mapped area showed no

change in the rock types, which are the coarse-grained gneiss with dolerite intrusions. However, the latter become much more abundant than in the mapped area.

The coarse-grained gneiss is traversed by a number of northerly trending shear zones in which the gneiss has been converted to a quartz-sericite schist. In the western part of the area these shear zones are much rarer, probably due to the presence of the incompetent bands of mica schist which would " take up " any shearing movement.

The ferruginous sandstone outcrops in the western part of the area and is invariably lateritised. Lateritised ferruginous sandstone and lateritised metamorphic rock are often found in close association and sometimes a single mesa consists of both types. From the field occurrence it appears that the contact of the ferruginous sandstone and the Pre-Cambrian metamorphics is irregular and that the former occurs as a thin discontinuous layer lying unconformably on the older rocks (text fig. 1). The outcrops of ferruginous sandstone shown on the map are those that were actually seen in the course of the traverses. However, as much of the laterite was mapped from aerial photographs, the extent of the ferruginous sandstone may well be greater than is shown.



Text fig. 1.

Diagrammatic section (not to scale) of the Wattle Flat area, showing the structure of the Pre-Cambrian complex and the relation of the later rocks to it.

The laterite, which is developed over both the Pre-Cambrian rocks and the later ferruginous sandstone, is not confined to any particular level or levels, but occurs at various heights from the highest laterite mesa, at an elevation of about 880 feet above sea level, to the banks of the Brockman River, about 600 feet above sea level (Plate II, fig. A). Furthermore, solid laterite cappings obviously formed in situ are sometimes seen dipping down towards the present valleys at angles of as much as 7°. The laterite mesas in the western part of the area often show 5 or 10 foot breakaways on their eastern margins, but slope gradually to the west until they grade into yellow sand, the contact not being marked by any breakaway.

The sand formation is found to the west of the main outcrops of Pre-Cambrian rocks and is believed to be younger than all the rocks previously mentioned. Its contact with the older rocks is extremely irregular and frequent large hills of Pre-Cambrian metamorphics stand out as prominent " islands " completely surrounded by a " sea of sand." For this reason it

is thought that the thickness of sand in the area is not very great. The sand is generally a light yellow colour and its vegetation includes abundant banksias. Banksia (*Banksia sp.*) is completely absent from the vegetation over the Pre-Cambrian and because of this and the light colour of the yellow sand, the contact between the two stands out very clearly both in the field (Plate II, fig. B) and on the aerial photographs. Included in the sand formation are areas where the sand is greyish-white in colour with laterite nodules, and from which the banksia is absent. It appears that this sand is a fairly thin layer overlying laterite, and this fact possibly accounts for the difference in vegetation. Elsewhere greyish-white sand with the typical banksia association is found overlying the yellow sand. Whether or not there is any difference in age or origin of the two types of sand is a matter for speculation.

IV. THE STRUCTURE OF THE PRE-CAMBRIAN COMPLEX.

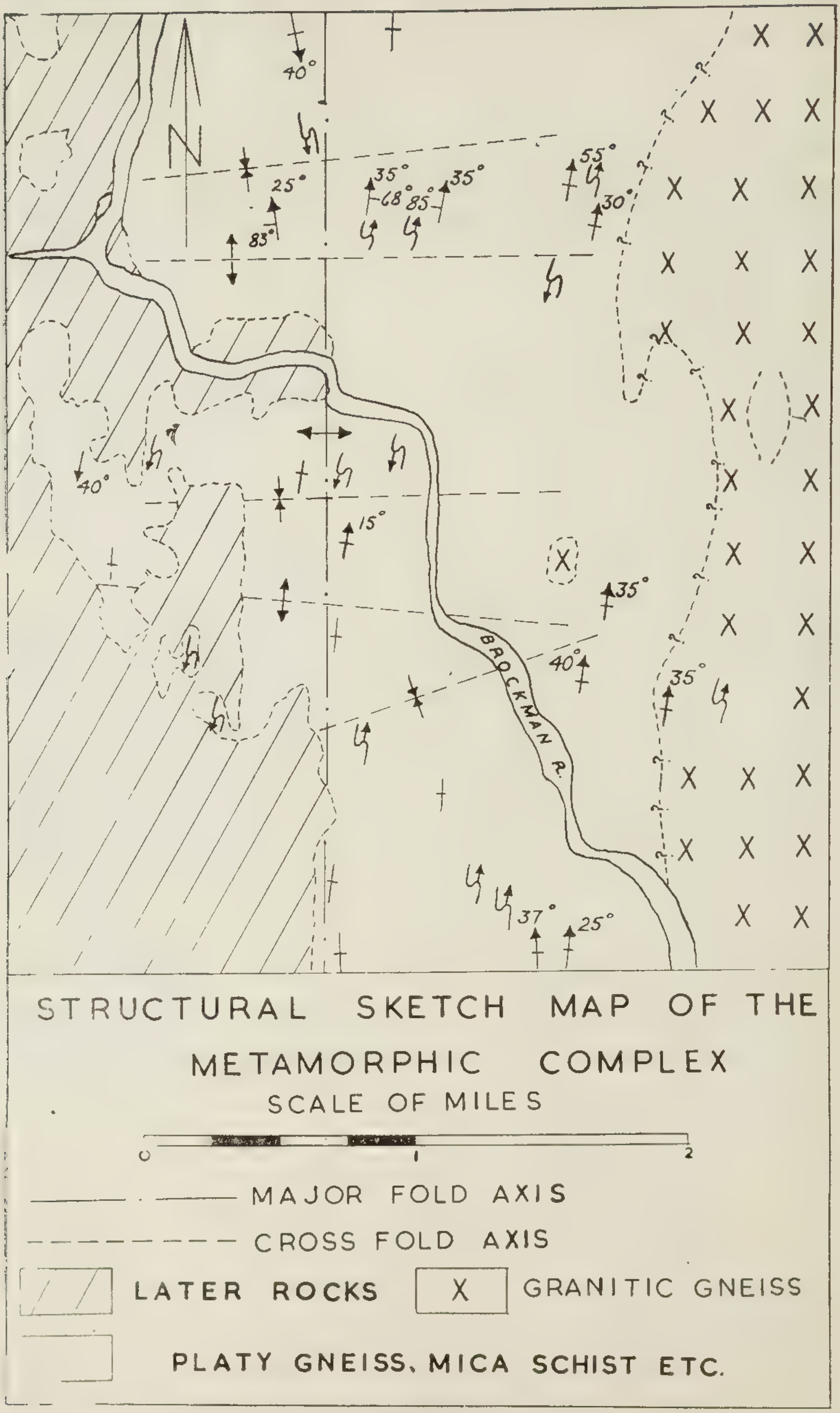
The strike of the rocks is practically north-south and variations of more than 12° from this direction are rare. The beds dip vertically, or very steeply, towards either the east or west. Owing to the large number of beds present, their variation in composition, their tendency to lens out along the strike, and the absence of any marker horizons, precise structural interpretations were rendered very difficult. The interpretation of the structure as given below was made on the basis of readings of drag folds and pitch.

Neglecting for the moment the effects of pitch and considering only the relative vertical movements indicated by the drag folds, it will be seen that to the west of a meridional line drawn about 20 chains west of Block 805 the readings on all the drag folds are west side up, indicating the west limb of an anticline. To the east of this line the readings on most of the drag folds are east side up, indicating the east limb of an anticline. However, one or two readings of drag folds in mica schist showed west limb structures. The possible reason for this is that minor west limb structures are superimposed on the major east limb structure. Such features as this naturally render drag fold readings rather inconclusive, but it seems reasonable to assume that somewhere in the vicinity of this meridional line a major anticlinal axis exists, about which the beds are isoclinally folded.

The pitch of the folds in the area is not constant, sometimes it is to the north, sometimes to the south. However, there is a certain amount of regularity about this change of pitch. In the extreme north of the area all the readings show a southerly pitch and a little further to the south the pitches are all in a northerly direction, and continuing towards the south of the area a succession of pitches to the south, then to the north, the south again and finally, at the southern boundary of the area, the rocks pitch to the north. Thus on the basis of these readings there appears to be a number of east-west crossfold axes, five in all, beginning with a synclinal axis in the north. The two most southerly of these axes appear to coalesce towards the east, as the pitches in the south-eastern corner are all to the north. The average angle of pitch in either direction is 30 to 40 degrees. In one case it is nearly vertical but this rapid local steepening of pitch is probably due to some eccentric minor structure as it is not seen anywhere else.

Thus, on the basis of drag folds and pitches an interpretation of th possible structure of the metamorphic complex has been given. In th absence of a greater number of readings the positions of the various axe

cannot be fixed with certainty, however the structure of the area can be succinctly stated as a series of metasediments, isoclinally folded in a north-south direction and traversed by a number of east-west cross folds (text fig 2).



Text fig. 2.
Structural sketch map of the metamorphic complex at Wattle Flat.

V. PETROGRAPHY.

A. THE PRE-CAMBRIAN ROCKS.

1. The Gneisses.

The gneisses are the most abundant rocks developed in the area. On the map (Plate I) they have been divided into granitic gneiss outcropping in the east and platy gneiss which occurs in the west. These are two convenient field names that serve to indicate the difference between the two types. In the extreme west of the Pre-Cambrian complex a gneiss occurs, which, although it exhibits certain differences from the typical granitic gneisses, is best classed with them. On the whole the granitic gneiss possesses a reasonable uniformity of texture and composition, whereas the platy gneiss is much more variable and includes several types. The contact shown on the map between the two gneisses is purely arbitrary, and indeed it is almost impossible to draw an accurate contact. To the north it is largely obscured by laterite and in the extreme south by alluvium. In the central portion of the area the western approach to the granitic gneiss is marked by a close intercalation of the two types rather than a definite contact. This state of affairs is maintained over a considerable distance, sometimes as much as half-a-mile.

(a) *The Platy Gneisses.*

These occur as bands intercalated with micaceous and basic schists and vary in width from 10 chains or more down to a few inches. As the schists frequently lens out along their strike, two separate bands of gneiss may often coalesce to form a single one. The platy gneisses vary widely in texture and composition and rapid variations across the strike are common. Such features make it impossible to map separately the different types of platy gneiss.

In various parts of the area, especially near the contact with the granitic gneiss, the various types of platy gneiss contain large porphyroblasts of oligoclase and microcline, which transgress the gneissosity and stand out prominently against the fine-grained groundmass.

A rather puzzling feature is the extremely fine grain of many of the platy gneisses. It would be expected that, under the high grade metamorphism to which these rocks have been subjected (as evidenced by the presence of kyanite), a coarser texture would have resulted from recrystallisation. The obvious answer to this seems to be that the later shearing that has evidently taken place was the cause of this fine grain. Whilst mylonitization of some of the platy gneisses has occurred, many of the finest grained rocks contain large subhedral felspar porphyroblasts which are comparatively unaltered and which transgress the banded structure. Although these felspars show small fractures they do not show augen structure. It would seem impossible for these felspars to retain this form while cataclasis reduced other grains to a fine groundmass, especially as the porphyroblasts show inclusions of this groundmass. Hence it appears that even under the high-grade metamorphism that prevailed, the fine grain of these rocks was preserved. It will be seen later that these porphyroblasts are thought to have been introduced after the formation of the original rock.

Although on the basis of mineralogical composition distinct types can be recognised among the platy gneisses, these grade imperceptibly into one another. The type specimens described below, however, are sufficient to give a full petrographic account of the different varieties.

(i) Quartz-oligoclase-microcline-biotite gneiss (24264)*.—This is a light-grey, even-grained rock with a distinct fine banding due to the alternation of thin biotitic and quartzo-felspathic bands and also to the parallel orientation of biotite flakes.

In thin section there appears to be, in addition, a parallelism between the long axes of quartz and felspar grains and the gneissosity. There is a tendency for some of the crystals to show peripheral granulation, other evidence of strain effects being the marked undulose extinction of the abundant quartz grains and the irregularity of the twinning in some of the plagioclase grains.

Albite-oligoclase and microcline are both abundant and myrmekite is also present.

The biotite shows strong pleochroism with X greenish-brown and Z very dark-brown. It appears to be altering to chlorite and iron ores.

One or two large subhedral grains of magnetite are present and minute needles of apatite and zircon occur in accessory amount.

Several varieties of the above type exist. Some specimens are quite rich in muscovite, others may show an absence of microcline or a paucity of biotite. A common variant is that in which microcline and albite-oligoclase occur as relatively large porphyroblasts. This association of porphyroblastic microcline and plagioclase has a genetic significance and a separate description of this rock (25704) is warranted.

This is light-coloured, fine-banded rock with occasional felspar porphyroblasts up to 3 mm. in diameter, transgressing the banding. Under the microscope it is seen to consist of a very fine groundmass of quartz and felspar grains, a mere fraction of a millimetre in size, parallel lenses of quartz grains of much larger size (averaging about 0.5 mm. in diameter) and occasional porphyroblasts of microcline and albite-oligoclase. These are squarish subhedral crystals, not augen, and they appear to have been formed by growth in the solid. The microcline porphyroblasts are larger and more abundant than those of the plagioclase. They are slightly kaolinized and contain frequent inclusions of quartz, muscovite, biotite and magnetite. The albite-oligoclase is clear, with albite twinning poorly developed. When present at all it is very irregular in shape.

Biotite is fairly abundant, occurring either as small subhedral to anhedral isolated flakes, or as much larger aggregates associated with muscovite, chlorite and iron ores. It appears to be altering either to a greenish pleochroic chlorite or to a dark opaque mass of iron ore and chlorite. The muscovite, often associated with the biotite, shows a faint greenish pleochroism.

The accessories are magnetite, ilmenite altering to leucoxene, with lesser amounts of zircon, apatite and sphene.

(ii) Garnetiferous gneiss.—In the fine-grained biotite-rich gneisses garnets find abundant and widespread development. Generally they occur in elongated bands showing a paucity in biotite, indicating that the garnet has developed at the expense of this mineral. A curious feature seen in the field is that these garnetiferous bands transgress the directed structure of the biotite gneisses in which they are developed at an angle of about 5 to 10 degrees—they have probably been developed along the traces of fracture cleavage.

* Specimen numbers refer to the General Collection of the Department of Geology of the University of Western Australia.

25667 is a light-coloured rock with large idioblastic garnets up to 2 cm. in diameter in a fine-grained groundmass of quartz and felspar with occasional biotite flakes. Microscopic examination shows that the groundmass is even-grained, with an average grain size of about 0.25 mm. The garnet exhibits typical sieve structure, being crowded with quartz inclusions. It is pale pink in colour and is traversed by an irregular system of fractures along which extensive iron staining has occurred. Together with the garnet, quartz and albite-oligoclase, mostly untwinned, make up the bulk of the rock. Biotite, occurring in anhedral flakes, is not very plentiful. It is usually associated with the garnet, either around its margins or included in it, and shows varying degrees of alteration to chlorite which modifies its pleochroic scheme. Some of this chlorite shows anomalous blue interference colours under crossed nicols. Scattered grains of magnetite sometimes included in the garnet, and a few tiny zircons, are present.

(iii) Quartz-oligoclase-biotite-hornblende gneiss (24256).—This is a very distinctly banded rock with alternating quartzo-felspathic and ferromagnesian-rich layers up to 2 mm. thick. In thin section, parallel alignment of biotite flakes and hornblende crystals is evident. Quartz and plagioclase, sometimes showing twinning, occur as anhedral grains. The plagioclase is clear, with frequent inclusions of small subhedral quartz grains. These two minerals are also associated in a myrmekitic intergrowth. The refractive index of the plagioclase is greater than balsam but less than quartz, its optical character is positive with $(+)2V = 88°$. The maximum extinction angle perpendicular to the 010 cleavage is about 5°. This data indicates an albite-oligoclase of composition about $Ab_{85}\ An_{15}$.

Elongated subhedral flakes of biotite up to 1 mm. in length are abundant. It shows strong pleochroism with X light-brownish green and Z very dark brown. Subhedral prisms up to 2 mm. long and basal sections of hornblende are also plentiful. It is often closely associated with the biotite and contains numerous inclusions of plagioclase, epidote and quartz. The pleochroic scheme is X brownish green, Y deep brownish green and Z deep blue-green, absorption $Z = Y > X$ and Z to $c = 19°$. Granular sphene is common, often forming small lenses which are usually associated with hornblende, biotite or epidote. The epidote shows similar occurrence but is less abundant than the sphene. Microcline is present in accessory amount only, other accessories being magnetite, apatite and zircon. Chlorite, pseudomorphous after hornblende, is a common secondary mineral.

(iv) Quartz-oligoclase-microcline-biotite-epidote gneiss (24261).—This is a prominently banded, medium-coloured rock, showing alternation of fairly thick biotitic and quartzo-felspathic layers. Examination of the thin section shows that the parallel orientated biotite flakes are associated with epidote. Although most of the quartz grains are only a fraction of a millimetre in size, occasional pockets of larger grains occur. Albite-oligoclase is found both as fine grains and as porphyroblasts up to 2 mm. in length. These show alteration, being crowded with fine granular zoisite. The porphyroblasts occasionally contain inclusions of the fine-grained quartzo-felspathic groundmass and some seem to be replacing microcline. They appear either to push aside or sharply truncate the groundmass constituents and their appearance indicates that they have grown in the solid state. Some of them have suffered small scale fracturing and bending of the albite twin lamellae. Myrmekite is present in small amount sometimes bordering microcline grains. The microcline, although less abundant than the plagioclase, is found as porphyroblasts and sometimes in the groundmass.

Biotite flakes averaging about 0.5 mm. in length are plentiful. The pleochroic scheme is the same as in the previously described gneisses and the mineral shows alteration to chlorite. Closely associated with, and included in the biotite is a pale yellowish green pleochroic epidote comprising about 15 per cent of the rock. Granular sphene is another common associate of the biotite. One or two basal sections of hornblende, altering to chlorite are present. Accessories include apatite, magnetite, calcite and zircon.

(b) *The Granitic Gneisses.*

Although certain minor variations do occur, generally speaking the granitic gneiss exhibits a uniformity that is not seen in the platy gneiss.

24250 is a grey, coarse-grained rock with a rather indistinct banding due to parallelism of occasional biotitic bands. It is crowded with felspar porphyroblasts up to 1 mm. in length, giving the rock a texture approaching granitic. Under the microscope these porphyroblasts are seen to be contained in a very fine-grained groundmass of quartz and felspar, with frequent parallel lenses of larger quartz grains. The general appearance of the rock is rather reminiscent of 25704 described above, the chief point of difference being the much greater proportion of porphyroblasts to groundmass in this specimen. The porphyroblasts contain inclusions of the fine-grained groundmass. Microcline, which shows a certain amount of kaolinization, is more abundant than the albite-oligoclase. The latter shows surface alteration to flecks of fine sericite. Greenish biotite, altering to chlorite and iron ores, and also a very pale green muscovite are present. Magnetite and ilmenite altering to leucoxene are the most common accessories, others being apatite, zircon and sphene.

24259 is a very similar specimen except that the banding is less distinct and the fine-grained groundmass less abundant.

Frequently the granitic gneiss is richer in ferromagnesians than the specimens described above. Dark clots and stringers, which under the microscope prove to consist of aggregates of biotite, chlorite and iron ores, are orientated parallel to the gneissic structure and give the rock a distinctly banded appearance. Small veinlets of deep purple fluorite are common in some of these gneisses and this mineral may prove useful in correlation of the gneisses.

In the western central part of the metamorphic complex a gneiss (25639d and 25640) occurs which in the field is similar to some of the granitic gneisses to the east. However, microscopic examination shows it to differ from the typical granitic gneisses in a number of respects and a separate description is warranted. Furthermore, this gneiss contains inclusions of a peculiar suite of basic rocks which will be described later.

In hand specimen it is coarse-grained and porphyroblastic with a very distinct banding due to alternation of quartzo-felspathic and thick biotitic layers. In thin section small amounts of a very fine-grained groundmass appear, as well as the large porphyroblastic crystals. Albite-oligoclase is by far the most abundant felspar, microcline being much less abundant and occurring in much smaller grains, usually occupying interstices between the large albite-oligoclase porphyroblasts and sometimes being enclosed by them. Myrmekite also is quite plentiful. Biotite is present in stout euhedral to subhedral crystals up to 2 mm. in length, often containing inclusions of quartz, plagioclase, apatite, epidote and zircons with pleochroic haloes, and showing strong pleochroism from greenish brown to very dark brown. The accessory minerals are calcite, sphene, apatite and epidote.

In the field this coarse-grained gneiss is seen to contain small concordant lenses of a fine-grained platy gneiss consisting of quartz, albite-oligoclase, microcline and biotite. A small pegmatite vein is seen transgressing the strike of the coarse-grained gneiss.

The peculiar feature about it is that the gneissic banding and the biotitic layers responsible for this banding continue right across the pegmatite vein, indicating that the latter is the result of gaseous emanations rather than a liquid intrusion.

Specimens of all the different gneisses in the area were examined under ultra-violet light for fluorescent effects. It was thought, following the recent work of Wilson (1947, p. 201 ; 1950) that the felspars of different varieties might have shown different fluorescent effects, forming some basis for correlation and possibly giving a clue to the mode of origin of these rocks. The results were rather disappointing, the only rocks containing fluorescent felspars being the coarse-grained gneiss just described. Under the ultra-violet light the albite-oligoclase showed a faint but definite pink and the quartz a bluish colour. The zircons in the biotite appeared as bright orange specks. The felspars of the pegmatite vein referred to and the gneiss both showed this pink fluorescence, indicating probably that the gneiss and pegmatite were genetically related. However, the felspars of a large pegmatite dyke a couple of chains distant showed no fluorescence, which may mean that this dyke is unrelated to the gneiss. Apart from suggesting that there may be some difference in origin between this gneiss and the main body of granitic gneiss to the east, the results of the fluorescence tests were too indefinite to warrant any conclusions being drawn.

2. Lenses in the Granitic Gneiss.

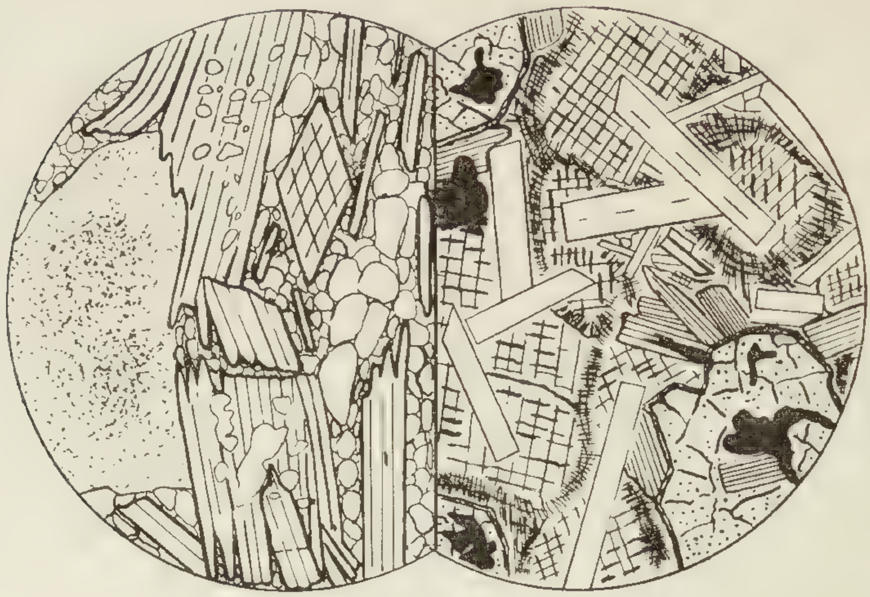
The frequent occurrence of lenses of platy gneiss in the granitic gneiss has already been referred to. In the extreme eastern part of the area a lens of the epidote-rich variety of the platy gneiss is found and at another spot a quartzite lens occurs. In addition to these there are three types of basic lenses described below. All the different types of lenses are concordant with the gneiss.

(a) *Hornblendic basic lenses.*

These occur frequently in the granitic gneiss and one specimen was found within the platy gneiss. They are dark-coloured, schistose rocks occurring as bands up to a chain or more in width and several chains in length. In the field they were mapped as sheared dolerites but petrographic examination suggests that they are of a different origin. Invariably they contain hornblende crystals in parallel alignment and usually fairly large porphyroblasts of albite-oligoclase. They are in fact hornblende schists, but it is proposed to reserve this name for a somewhat different group of rocks.

24238 (text fig. 3A) is a dark-coloured, schistose rock. It is by no means uniform in texture, for although the most abundant constituent is hornblende, there are quite sizeable light-coloured bands of quartzo-felspathic material and in addition scattered felspar porphyroblasts up to 2 mm. or more in diameter.

In thin section this heterogeneity becomes even more evident and the rock is seen to consist of hornblende-rich and quartz-felspar-rich aggregates which show a crude alternation of layers. There are, in addition, the porphyroblasts of felspar which appear to displace and often include the other minerals.



Text fig. 3.
Two types of basic lenses. Fig. 3A is a hornblendic basic lens, showing hornblende laths in parallel alignment, a fine quartzo-felspathic aggregate, and saussuritized porphyroblastic oligoclase. Fig. 3B is a garnetiferous biotite pyroxenite, showing ophitic texture with plagioclase laths included in pyroxene which is altering to fibrous hornblende around its margins. Other constituents seen are idioblastic garnets, cored by magnetite, and biotite laths.

The prophyroblasts include saussuritized albite-oligoclase and microcline, which occurs as smaller grains and is much less abundant than the plagioclase. The hornblende is usually in the form of parallel, elongated subhedral laths of varying size. Some of the larger crystals are markedly poikiloblastic containing numerous inclusions of fine quartzo-felspathic material. It is strongly pleochroic with X yellowish green, Y deep brownish green and Z deep bluish green, with the absorption Y > Z > X. Chlorite from the alteration of hornblende is quite plentiful. It is biaxial negative with (—)2V about 30°. Associated with the hornblende are occasional aggregates of greenish chloritized biotite. Small amounts of magnetite changing to hematite and skeletal crystals of ilmenite altering to leucoxene are also associates of the hornblende. The quartzo-felspathic part of the rock, other than the porphyroblasts already mentioned, consists of a very fine granular aggregate with lenses of quartz grains of considerably larger size. It is indeed very similar to the groundmass of the platy gneisses. Apatite is present in the rock in accessory amount.

(b) *Chlorite-biotite schist* (25672b):

This is of much rarer occurrence than the hornblende lenses and was in fact, found at only one place. It is a dark-coloured micaceous rock with a schistose structure and is traversed by quartz veins arranged parallel to the schistosity.

Microscopic examination shows it to consist of long subhedral laths of biotite, alternating and associated with elongated aggregates of chlorite. The biotite is pleochroic according to the scheme—X very light brown and Z very dark brown—and it contains numerous inclusions of granular sphene and apatite, also a little quartz and epidote. The chlorite is pleochroic from

pale green to emerald green and under crossed nicols shows an anomalous greyish blue interference colour. Also associated with the biotite are small amounts of muscovite. The quartz veins are composed of grains of average size 0.5 mm., which have undulose extinction and in most cases serrated edges, indicative of crushing.

(c) *Garnetiferous greenstones and associated biotite norite.*

Occurring as lenses in the previously mentioned coarse-grained gneiss from the western central part of the metamorphic complex are a few peculiar basic rock types which appear to be genetically related. The largest of these lenses is about 4 chains wide and contains what appears to be a large drag-fold in which a definite pitch to the south is seen. Rock types present in this lens are a dark, medium-grained, even-textured rock which might be referred to as a hornblende diorite, passing on its margins into a hornblende schist. This schist does not appear to have any genetic significance other than the fact that it had developed from the massive rock due to marginal stress. A garnetiferous biotite pyroxenite is also present. The hornblende diorite just referred to is not given a separate description here because, other than the absence of garnet, it is similar in all respects to a garnetiferous biotite amphibolite which is found underlying the laterite a few chains to the south and which is described below.

A few chains to the west of this large basic lens there are two smaller lenses consisting respectively of biotite norite and garnetiferous biotite pyroxenite. The biotite norite was not found at any other place in the area but about a mile to the north-east of these lenses a specimen of garnetiferous biotite pyroxenite was collected from a lens in the platy gneiss.

The garnetiferous biotite pyroxenites are in hand specimen (25652) almost identical with dolerite and under the microscope they show a distinct ophitic texture, the only apparent difference from a dolerite being the presence of idioblastic garnets and fairly plentiful brown biotite. Even so, the temptation is strong to call them dolerites of abnormal composition, possibly contaminated. However, in view of their apparent genetic association with the rock types mentioned and the fact that the folded and pitching structure referred to above occurs in these rocks, they are best regarded as basic lenses in the gneiss. A discussion of their possible modes of origin will appear below.

25652 (text fig. 3B) is a typical *garnetiferous biotite pyroxenite.* It is a dark, fine even-grained, massive rock which under the microscope shows an ophitic texture. Plagioclase appears as strongly normally zoned, clear, subhedral laths. Albite twinning is seen in almost all the grains, the maximum extinction angle in sections perpendicular to the 010 twin plane being 28°. The optical character is positive with a variable 2V. It appears as though the average composition is near Ab_{50} An_{50} (labradorite). Clinopyroxene occurs as subhedral grains invariably altering to hornblende around the margins. It shows good cleavage, a fine schiller structure and twinning along the 100 plane. Inclusions of plagioclase are present. It is optically positive with (+)2V about 40° to 45° but variations from this occur. It is possibly a diallagic ferro-augite. Also present and sometimes coring the clinopyroxene is a small amount of hypersthene. Its pleochroism is not marked, it is optically negative with 2V about 75° and is therefore an iron-rich variety.

Hornblende is seen both as a fine border around the pyroxene and as quite large anhedral grains showing a good amphibole cleavage. It is pleochroic with X pale green, Y olive green and Z green and $Z \geq Y > X$. Garnet is fairly abundant as pink idioblasts up to 1 mm. in diameter, almost invariably cored by magnetite associated with brown biotite. It also contains small inclusions of altered pyroxene and plagioclase. Anhedral grains of quartz and needles of apatite are present in accessory amount.

24239 is a *garnetiferous biotite amphibolite* which in hand specimen is a dark, medium-grained, massive, even-textured rock. Under the microscope it is seen to consist mainly of anhedral grains or laths of albite-oligoclase with marked normal zoning, and granular to poikoloblastic aggregates of hornblende, which contain abundant inclusions of plagioclase and less frequent magnetite and garnet. Also included in the hornblende are a number of hematitic aggregates. Often found as cores in these are tiny relics of pyroxene, which give an optically positive figure with a moderately large 2V. From this it seems as though the hornblende has developed from the pyroxene. Garnet is quite plentiful as pink idioblasts up to 2 mm. in diameter. It is almost always cored by magnetite and contains in addition, hornblende and plagioclase inclusions. Brown pleochroic biotite is found usually associated with the hornblende. Chlorite altering from hornblende is present and accessories are quartz and apatite.

25656 is a *biotite norite* which in hand specimen is a dark-coloured, medium-grained, even-textured rock. In thin section the rock is seen to consist essentially of subhedral laths of labradorite showing frequent albite and Carlsbad twinning, pyroxene and hornblende. Hypersthene is the most abundant pyroxene, occurring as anhedral to subhedral grains showing very fine schiller inclusions. The extinction is mostly parallel but deviations of a few degrees from this are seen. It is faintly pleochroic from pale pink to pale green and it is optically negative with 2V about 60°, which puts it into the iron-rich category. It is altering to hornblende around its rims. Also present, occurring in the same manner, but much less abundant than the hypersthene, is optically positive clinopyroxene, with $Z \wedge c = 45°$. Hornblende is abundant occurring both as fine borders around the larger pyroxene grains and as granular aggregates. It is pleochroic with X pale green, Y brownish green, Z olive green and absorption $Y > Z > X$ and $Z \wedge c = 26°$. Biotite occurs as subhedral flakes up to about 0.5 mm. in length, generally associated with the amphibole. It is strongly pleochroic with X pale straw yellow and Z dark brown. Anhedral grains of magnetite, sometimes changing to hematite, are also usually associated with hornblende. Apatite is present in accessory amount.

3. Shear Zones in the Gneiss.

As mentioned before these are confined mainly to the granitic gneiss in the east and the platy gneiss immediately adjacent to it. They have a general northerly trend and their effect is to reduce the gneisses to quartz-sericite-chlorite schists (25690).

This is a light reddish-grey rock with a pronounced schistose structure. It shows an alternation of fine micaceous bands with bands and lenses of crushed quartz. Muscovite occurs both as fine sericite aggregates and small subhedral flakes with a good cleavage. It is intimately associated with a greenish biotite, most of which has altered to chlorite. Ilmenite altering to leucoxene and magnetite changing to hematite are quite abundant accessories.

4. The Mica Schists.

Next to the gneisses these rocks are the most abundant in the metamorphic complex. They occur in bands varying from a few feet to several chains in width. On the whole the bands of mica schist are not as wide as those of the gneisses and they have a greater tendency to lens out along their strike. Here it may be mentioned that for obvious reasons the smaller outcrops of schist are not shown on the map.

The variations in the mica schist are mainly mineralogical and they can be conveniently classified according to the minerals present into mica schists, garnet-mica schists, staurolite-mica schists and kyanite-mica schists. Apart from the mica schists, by far the most abundant of these are the kyanite-mica schists, staurolite being found in a few specimens only and garnet in contrast to its abundant development in the platy gneisses, was found in only one specimen.

On one of the field excursions, at which the author was not present, a rock was collected, which on examination proved to be a quartz-biotite-epidote schist. It was found as loose boulders in an area that is shown on the map as granitic gneiss near the contact with platy gneiss. A later inspection of the area failed to reveal any trace of this rock and so its field relations are not known, but it is evidently not of widespread occurrence. A petrographic description of the rock is given but in view of the above facts no speculation is made as to its mode of origin.

(a) *Mica Schist.*

The mica schists, and indeed the other members of the metapelitic schist group, may contain both biotite and muscovite, or either one of these minerals may be absent.

24271 is a quartz-muscovite-biotite schist and is typical of the mica schists. It is a light-coloured, very schistose rock consisting of muscovite and biotite bands intercalated with lenticular pockets of quartz, the grains of which average about 0.5 mm. in diameter and show undulose extinction. The biotite is pleochroic with X almost colourless and Z brown. The absorption in both directions is less than is the case in all of the rocks previously described. It occurs as elongated flakes intimately associated with similar shaped muscovite flakes. Small zircons with intense pleochroic haloes are common inclusions in the biotite.

(b) *Garnet-mica schist.*

25695, a garnet-muscovite schist, is the only representative of this group found in the area. It is an iron-stained very schistose rock, with layers of muscovite and quartz and frequent idioblasts of garnet about 0.5 cm. in diameter. Quartz occurring as anhedral grains with undulose extinction and average size of 0.5 mm. is the most abundant constituent. The elongated aggregates and flakes of muscovite are often very much iron-stained. The large garnets are also iron-stained and are crowded with quartz inclusions, which curiously enough, show much more regular outlines than the quartz grains that are not included in the garnet, almost as though the rock had once been in a plastic state and that the garnets had protected their quartz inclusions from the later cataclastic movements that had been responsible for producing the irregular margins of the rest of the grains. Magnetite changing to hematite is an abundant accessory in the rock, and tiny apatites and zircons are also present.

(c) *Staurolite-mica schist.*

25658 is a quartz-muscovite-biotite-staurolite schist and consists of bands of muscovite and biotite flakes intercalated with sizeable veins and pockets of quartz. Large idioblasts of staurolite up to 2 cm. or more in length and containing quartz inclusions are common. Biotite, altering to chlorite and iron ores and pleochroic from light green to dark brown occurs as elongated subhedral flakes together with lesser amounts of muscovite. The staurolite is crossed by irregular fractures and frequently contains quartz inclusions. It is optically positive with 2V about 88°. It is strongly pleochroic according to the scheme X very pale yellow, Y pale brown and Z reddish-brown, with absorption $Z > Y > X$. Accessory minerals are magnetite changing to hematite and apatite.

(d) *Kyanite-mica schist.*

In the majority of cases the kyanite-mica schists are similar to the mica schists except that they contain abundant large bladed crystals of kyanite up to 3 cm. in length. In some specimens, however, the kyanite crystals are much smaller and less evident in hand specimen.

(e) *Quartz-biotite-epidote schist* (24274).

This a dark grey finely banded schistose rock with quartz veins both parallel and oblique to the schistosity. Under the microscope bands of quartz are seen alternating with very fine biotitic bands containing epidote and sphene. The grain size of the quartz varies from a small fraction up to about 1 mm. in length. The larger grains are usually much longer than they are wide, and their long axes parallel the schistosity. The biotite, pleochroic from pale greenish brown to very dark brown occurs as numerous extremely fine layers parallel to the schistosity. Associated with the biotite are bands composed of granules of epidote, with sphene present to a lesser extent. Irregular aggregates of pale green chlorite also occur in the rock.

5. Quartzite.

Quartzites are comparatively rare in the metasediments of Wattle Flat. A band in the north of the area, about a chain wide and extending for a known distance of half-a-mile and a smaller lens in the granitic gneiss constitute the only sizeable outcrops encountered.

25705 is a greyish coloured, distinctly banded, highly quartzose rock. Under the microscope the banding is seen to be due to alternation of quartzose layers containing numerous small laths of biotite with layers consisting almost entirely of quartz. The banding is also due in some respect to the parallel alignment of the biotite laths, and to the alternation of bands of different grain size. Quartz comprising about 80 per cent of the rock is found as anhedral grains averaging 0.25 mm. in diameter and showing serrated edges and undulose extinction. Biotite and muscovite occur as minute laths, which are confined to certain bands and which are in parallel alignment. These laths often continue through or are included in the quartz grains. The biotite is pleochroic from pale greenish brown to very dark brown and is more abundant than the muscovite. Accessories include a small amount of untwinned albite and ilmenite altering to leucoxene.

6. Amphibolite and Epidote Amphibolite.

These rocks are found at only one place (157 N., 45 W.) where they are closely associated and intercalated with platy gneiss (hornblendic variety).

24248 is an amphibolite, similar in many respects to the hornblende schists, a group of rocks which are described below, but in view of some of its characteristics, and its association with the epidote amphibolite, it is thought to be of different origin. In hand specimen the rock is medium to coarse grained with a marked schistose structure. In thin section it is seen to consist of about 85 per cent of hornblende occurring as euhedral basal sections and prisms up to 0.5 cm. in length, and containing abundant inclusions of magnetite and a few of plagioclase. It has rather a peculiar pleochroic scheme with X pale green, Y emerald green and Z blue, absorption $Z = Y > X$ and $Z \wedge c$ of 29°, which is rather high for an amphibole. Basic andesine comprises about 10 per cent of the rock and the accessories include apatite, epidote and sphene.

24249 is an epidote amphibolite and consists of a dark green part consisting almost entirely of hornblende laths, included in which are many irregular shaped light green patches of granular epidote varying in size up to about 6 cm. in length. These epidotic patches contain isolated laths of hornblende. In thin section it is seen that these two minerals together with magnetite comprise the entire rock, no quartz or felspar being present. The hornblende laths are subhedral, varying in size up to 2 mm. and show a very rough subparallel alignment. Pleochroism is marked with X light yellow-green, Y green and Z blue with absorption $Z = Y > X$ and $Z \wedge c$ of 27°. The similarity of optical properties of the hornblendes of this and the previous specimen is apparent. The epidote occurs as aggregates of fine grains, varying in size up to 0.5 mm. It is non-pleochroic and optically negative with 2V about 88°. Magnetite is fairly abundant, occurring as anhedral grains of varying size.

7. Hornblende Schist.

This is quite abundant as bands, rarely exceeding a chain in width, intercalated with the platy gneisses and mica schists. Usually they do not persist for any great distance along their strike. Petrographically they show a uniformity of texture and mineral composition.

25687 is a dark-coloured, even-grained rock with a marked schistose structure due to alternation of felspathic and hornblendic bands and to parallel alignment of hornblende prisms, which vary in length up to 3 mm. In thin section the hornblende is seen to be strongly pleochroic with X pale yellow-green, Y olive green, Z bluish green, absorption $Z > Y > X$ and $Z \wedge c$ of 23°. It often contains inclusions of quartz, oligoclase, sphene or epidote. Some of it has altered to chlorite. Albite-oligoclase occurs in anhedral grains elongated parallel to the schistosity and frequently shows albite twinning. It is fairly clear and may contain a few inclusions of hornblende or epidote. Anhedral grains of quartz are of fairly frequent occurrence, granular bands of epidote and sphene are common whilst magnetite and apatite are present in accessory amount.

8. Uralitized quartz dolerite.

This is found as dykes, of average width about a chain, intruding the earlier rocks. Generally they trend in a N.N.W. direction.

24242 is a dark green, fine even-grained rock. In thin section it is evident that is has suffered considerable alteration but a sub-ophitic texture is preserved. Basic andesine occurs as markedly zoned subhedral laths with a faint brown colour and shows general saussuritization. The pyroxene appears to have been entirely replaced by a light greenish, fine, fibrous uralitic hornblende. Accessories include ilmenite altering to leucoxene, anhedral flakes of brown biotite, often associated with the ilmenite and a few small anhedral grains of quartz.

9. Breccia.

This rock was found as loose boulders on the surface at 95S., 30E., an area that consisted of platy gneiss and mica schist and it is not known whether its relation to these rocks is concordant or discordant.

In hand specimen it is a dark green, fine grained, fragmental cherty looking rock without any trace of banding. In thin section the fragmental nature of the rock is even more striking. It consists of extremely fine angular fragments of quartz and felspars embedded in a groundmass of fine fibrous amphibole and chlorite. Large irregular patches of granular sphene and opaque leucoxene are present. Pale greenish yellow pleochroic epidote is quite abundant and the whole rock is traversed by a network of minute veinlets of quartz and felspar. The felspar is optically positive and its refractive index is approximately the same as Canada balsam and so it is probably an albite-oligoclase. It shows marked zoning but no twinning. Also present is a colourless mineral of low birefringence, refractive index less than balsam, optically negative with 2V about 65°, which is possibly orthoclase. The hornblende usually occurs in fine fibrous form but one or two larger poikiloblastic crystals up to 1 mm. in length are present. It shows pleochroism X pale yellow-green, Y olive green, Z blue-green and absorption $Y > Z > X$. Much of the hornblende shows partial or complete alteration to chlorite. Numerous minute needles of apatite are present in accessory amount.

B. THE LATER ROCKS.

1. Ferruginous Sandstone.

The ferruginous sandstone is a fine-grained non-bedded, unfossiliferous, reddish-brown rock. The alumina and iron oxide content of the rock is very high and the detrital quartz grains are well sorted, the majority of them being retained on the 115 Tyler mesh with a smaller amount on the 250 mesh. Larger grains than this, however, are present in the ferruginous sandstone and in fact quartz pebbles are sometimes found in the lateritised ferruginous sandstone.

An examination of the finer grains which compose the majority of the detritals, shows that they are angular with vitreous and fractured surfaces. Sphericity determinations show no significant variation, the sphericity of the majority of the grains being between 0.70 and 0.85 on the visual scale of Rittenhouse (1943).

Heavy minerals were separated from the grains retained on the 115 and 250 mesh sieves. They are fairly plentiful and include :—

Ilmenite : which is by far the most abundant of the heavy minerals and is invariably altering to leucoxene. Generally, the grains are poorly rounded with ragged edges.

Hematite : rather similar in occurrence but less abundant than ilmenite. It shows a reddish colour in reflected light.

Magnetite : this is much less abundant than ilmenite or hematite. Occasionally it occurs as well rounded grains.

Kyanite : the most plentiful of the non-opaque minerals is kyanite. It is found mainly as subhedral prisms and does not show rounding.

Staurolite : is quite abundant in irregular shaped grains, pleochroic from pale yellow to yellowish-brown.

Zircon : almost invariably occurs as euhedral grains, which are colourless or slightly purplish and often zoned.

Andalusite : is found as irregularly shaped grains.

Muscovite : one or two irregular flakes are present.

Tourmaline : a few unrounded grains showing strong pleochroism are present. Both blue-grey and brown varieties are seen.

Sphene : one or two irregular grains only are present.

2. Laterite.

The chief variations in the laterite are in structure (which may be cellular or pisolitic), relative proportions of iron oxides and aluminous materials and in the presence or absence of quartz pebbles. Generally the laterite overlying the ferruginous sandstones can be distinguished from the laterite overlying the Pre-cambrian, in that the former contains included ferruginous sandstone fragments.

In the north-east part of the area laterite from a high mesa overlying platy gneiss, exhibits polar magnetic properties, and compass readings made at this point show very marked deviations. Moreover some fragments are capable of attracting and repelling the compass needle, that is, they possess North and South poles. Some specimens collected from outcrops in situ show different polarity on their upper and lower faces (the upper being a south pole). Other specimens from nearby do not show any marked magnetic effect.

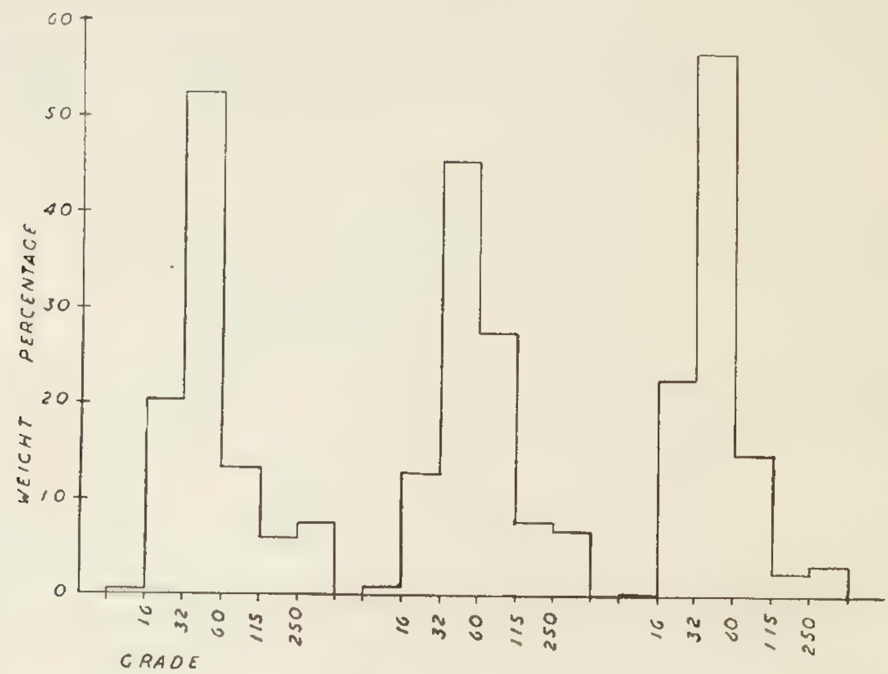
Two other laterite outcrops in the area, further to the west, cause a deviation of the compass needle but this is less marked and it is not known whether these laterites possess polar properties.

The rocks underlying the polar magnetic laterite are platy gneisses intruded by a dolerite dyke, but whether these can be in any way responsible for the magnetic phenomenon is very doubtful.

3. The Yellow Sand Formation.

Mechanical analyses and heavy mineral separations of three different samples of sand from different places in the area were made. In addition the quartz grains were examined for roundness, sphericity and surface texture. All three samples showed a marked similarity of properties and a separate description of each is not warranted.

In all three specimens the maximum amount (45 to 55 per cent) of grains are retained on the 60 Tyler mesh (text fig. 4 for histograms). The sorting coefficients of the samples vary from 1.3 to 1.4 so that according to Trask's classification they are well sorted. However, the sorting is not as good as in the ferruginous sandstone. The coefficients of geometrical quartile skewness of the three specimens are 0.79, 0.94 and 1.10 so that in two of them the maximum sorting lies a little on the coarse side of the median diameter and in the other a little on the fine side.



Text fig. 4.

Histograms showing the mechanical composition of the three sand samples examined.

Variations in roundness and surface texture of the grains can be summarized as follows :—

Retained on 16 mesh (1–2 mm.).—All the grains are frosted on the surface and are fairly well rounded (between 0.5 and 0.6 on the visual scale of Krumbein, 1941).

Retained on 32 mesh ($\frac{1}{2}$ to 1 mm.).—The great majority of the grains show frosting and fair rounding, but a few are vitreous with rough fractured surfaces.

Retained on 60 mesh ($\frac{1}{4}$ to $\frac{1}{2}$ mm.).—Three types of grains can be distinguished, the fairly well rounded grains with the frosted surfaces seen in the coarser grades, fairly well rounded grains with a polished surface imposed on a frosted surface and finally, comprising about 50 per cent of the fraction angular vitreous grains with a rough fractured surface.

Retained on 115 mesh ($\frac{1}{8}$ to $\frac{1}{4}$ mm.).—Practically all the grains are the vitreous fractured type and only a few show frosted surfaces.

Retained on 250 mesh (1/16 to $\frac{1}{8}$ mm.).—Almost all the grains are the vitreous fractured type.

Thus it can be seen that the rounded and frosted grains tend to occur in the coarser grades and the vitreous fractured grains in the finer grades. There does not appear to be any gradual transition from one type to the other.

The sphericity of the grains of various grades shows no significant variation. In all grades the sphericity of the grains varied from about 0.70 to 0.90 on the visual scale of Rittenhouse (1943).

Heavy minerals were separated from the 60-115 and 115-250 mesh grades. The weight percentages of the three samples constituted by these heavy minerals were 0.1 per cent, 0.16 per cent and 0.28 per cent. On the whole the strongly magnetic fraction shows a marked angularity of grains whereas most of the non-magnetics are fairly well rounded. The minerals present include :—

Ilmenite : is the most abundant heavy mineral present. All the ilmenite shows some alteration to leucoxene, and in some cases this alteration is complete. Where there has been little alteration the grains are mostly angular with rough surfaces, showing percussion marks, but the grains that have completely altered to leucoxene are much more rounded.

Magnetite : is not as abundant as ilmenite, but nevertheless is quite plentiful, occurring as angular grains.

Hematite : is present as fairly well rounded grains.

Kyanite : is the most abundant of the non-opaques. It occurs as prismatic grains, the ends of which are generally fairly well rounded. Quartz inclusions are often present in the mineral.

Staurolite : the grains are mostly angular, especially in the finer fraction.

Zircon : the majority of the grains are colourless or slightly purple, well rounded and zoned. However, some euhedral zircons, containing small inclusions are also present.

Epidote : is seen as irregular grains with a marked yellowish green pleochroism.

Rutile : is present as dark reddish-brown grains showing varying degrees of roundness.

Tourmaline : the grains are dark brown, show strong absorption, but are not very abundant.

Andalusite : one or two well rounded grains showing pale pink pleochroism are present.

Hornblende : a few dark green grains are present.

Pleonaste : occurring as blue-green isotropic grains is rare.

VI. DISCUSSION.

A. THE PETROGENESIS OF THE PRE-CAMBRIAN ROCKS.

1. The Gneisses and the Basic Lenses in the Granitic Gneiss.

The platy gneisses, exhibiting as they do such features as intimate intercalation with mica schists, infinite variety of texture and mineralogical composition and rapid change in character across the strike, must be regarded as being of sedimentary origin. Originally they were a series of arkoses,

arkosic sandstones and greywackes, which have been subjected to intense folding and regional metamorphism, with the resultant formation of para-gneisses. The variations in the gneiss are due to facies variation in the original sediments. Hornblende and epidote gneisses, for example, are probably derived from sediments that contained a certain amount of dolomitic and calcitic material, whereas biotite-rich gneisses are due to the presence of a greater proportion of shaly material in the original sediment.

What then is the origin of the granitic gneiss ? Before answering this question, certain important facts may bear re-emphasis. Firstly, the strike and dip of the granitic gneiss is in all places essentially the same as that of the platy gneiss and associated metasediments. Furthermore, the granitic gneiss contains a number of lenses which include platy gneiss, quartzite and various types of basic rock. In all cases these lenses have a concordant relation to the enclosing granitic gneiss. Thirdly, no sharp contact is seen between the granitic and the platy gneiss, rather is there an intercalation of the two types. Finally, there is development in the platy gneiss, especially near the contact with granitic gneiss, of a number of porphyroblasts of microcline and albite-oligoclase. As mentioned previously, these transgress the bedding, contain inclusions of the groundmass and generally exhibit features indicative of their having grown in the solid state. Also, microscopic examination shows that the same fine-grained groundmass that is characteristic of some of the platy gneisses, is present in lesser amount in the granitic gneiss. Indeed, certain specimens of platy and granitic gneiss appear to differ only in the much greater proportion of porphyroblasts in the latter.

All of these facts are best explained by assuming that the granitic gneiss was originally a part of the same series of sediments that are now represented by the platy gneisses and micaceous schists. During the period of orogeny these sediments are thought to have been subject to a process of granitization which followed in the wake of the folding and regional metamorphism. The term " granitization " is used here in the sense that it is used by Read (1944), viz., " the process by which solid rocks are converted to rocks of granitic character without passing through a magmatic stage." This granitization included introduction by ionic diffusion of a large amount of felspathic material, resulting in the formation of the numerous porphyroblasts of microcline and albite-oligoclase. Parts of the country rock that escaped this granitization remained as lenses of platy gneiss in the granitic gneiss. The development of porphyroblasts extended beyond the granitic gneiss and is seen to a lesser extent in the surrounding platy gneiss. Associated with the granitization, probably as an end phase, was the formation of the ubiquitous quartz veins and the pegmatite dykes. These are thought to have been formed by metasomatic replacement rather than the intrusion of an end phase of a granitic magma (Ramberg, 1949). There is evidence (outlined above) that at least one pegmatite vein could not have been due to a magmatic intrusion. Indeed, it does not appear necessary to ascribe a magmatic origin to any of the gneisses in the area.

Before leaving this subject of granitization, the origin of the basic lenses will be considered. In the field the hornblende lenses were first thought to be sheared dolerites, but petrographic examination indicates that this is very unlikely. The hornblende-rich parts alternate with fine quartzo-felspathic aggregates very similar to the groundmass of many of the platy gneisses and there is also a development of large plagioclase porphyroblasts up to 2 mm. in diameter. It is inconceivable that such features could have developed

from the shearing of a dolerite. Furthermore, the presence in one or two specimens of porphyroblastic microcline, together with biotite, indicates a larger amount of potash than a normal dolerite contains. If then, the rocks are not sheared dolerites, we must look for another mode of origin.

Reynolds (1946) has suggested that the process of granitization involves a preliminary stage of enrichment in the cafemic constituents and alkalies. These elements are driven ahead of the main front of granitization as a basic front. If the front of granitization outstrips this basic front the basified rock will be caught up as concordant xenoliths in the granite.

It is thought possible that the basic lenses in the gneiss at Wattle Flat may have been formed in such a way, and that a basic front caused the formation of the hornblende, together with sphene, which is quite abundant in many of the specimens. These newly formed minerals were intercalated with the fine quartzo-felspathic groundmass of the original sediment. Subsequently these basic rocks were caught up in the advancing front of granitization and it was at this stage that development of the porphyroblasts occurred.

Basic lenses containing porphyroblasts similar to those developed in the enclosing gneiss are common features of gneissic complexes the world over. Numerous examples have been quoted by Reynolds (1946).

At this stage it may be argued that if one is to regard these basic lenses as products of a basic front, might not those platy gneisses that are rich in hornblende epidote or sphene, be a result of the same process, rather than the regional metamorphism of dolomitic and calcitic sediments ? This must be regarded as a possibility. In this connection Reynolds (1947) discusses the substance of a paper by Lapadu-Hargues, appearing in the *Bull. Soc. Geol. France.* Lapadu-Hargues considers that the various metamorphic grades are not isochemical as has been generally regarded and finds a variation exists in the concentrations of the various elements in rocks of different regional metamorphic grades. This he thinks is due to the difference in mobility of the various elements under metamorphic conditions. Iron and magnesium, for example, being the most mobile, become concentrated in the lowest metamorphic grade. Reynolds compares this with the " basic front " concept. If these theories are valid, then the relation between granitization, with its complementary basification, and regional metamorphism, may be very close.

How now are the garnetiferous greenstones and associated types to be explained ? It has been pointed out that despite the ophitic texture of some of them and general resemblance in hand specimen to dolerites, they could hardly be regarded as such.

Reynolds (1946) discusses the metasomatic alteration of pelitic and related rocks that are associated with granite and gives a number of examples. She points out that many granitic and granodioritic masses are walled and roofed by basic rocks which are also found as inclusions in the granite, and considers that these are due to the enrichment of pelitic sediments by elements of the basic front which travels ahead as the vanguard of a front of granitization. In many cases these basic rocks may assume the composition and appearance of igneous rocks for which they may be easily mistaken. As an example she draws attention to the Flamanville Granite of Normandy described in 1893 by Michel Levy, who was much impressed by the presence

of basic hornfelses containing pyroxene, amphibole, garnet, plagioclase, orthoclase, anorthoclase and sphene. At certain points these hornfelses exhibited an increase in grain size and passed to rocks resembling true dolerites, and granular diabases within which ophitic texture is locally developed. Reynolds quotes from Michel Levy " Nous voyons naître ainsi en petit, et par métamorphisme de contact du granite, des roches basique éruptives analagues aux diabases ouralitisées du Beaujolais, du Lyonnais, de la Loire et du Pûy-de-Dôme."

With the exception of orthoclase and anorthoclase, all the minerals mentioned above by Michel Levy are present in the garnetiferous greenstones at Wattle Flat, and his remarks on texture find a close parallel in these rocks. The point that arises from this discussion is the fact that a rock may exhibit all the textural characteristics of a typical igneous rock, including an ophitic relation between the plagioclase and pyroxene, and yet still be of sedimentary origin.

It is possible that the garnetiferous greenstones and associated biotite norite of Wattle Flat may be the result of metasomatic alteration of pelitic sediments by elements of a basic front that was associated with the granitization which is thought to have been responsible for the formation of the surrounding granitic gneiss.

An alternative hypothesis to this is that these rocks represent an early basic lava, intruded as a sill, contaminated with aluminous material and subsequently folded and regionally metamorphosed along with the sediments. However, the presence of kyanite in nearby micaceous schists indicates that during the folding of these sediments a high directed pressure prevailed. If these basic rocks were due to contamination of an early lava, it is difficult to see how such typical anti-stress minerals as hypersthene and clinopyroxene, which they contain, could survive in the presence of such a high directed pressure. The presence of these minerals indicates that the rocks in question were formed after the most intense folding and directed pressure had waned, that is about the middle or end stages of the main orogeny, and about the time of formation of the synchronous gneiss.

Before leaving this subject, mention should be made of the gneiss enclosing these garnetiferous greenstones. It was seen that this gneiss exhibits fluorescent effects not observable in other gneisses. This may be due to a local difference in chemical composition rather than a difference in age or origin. Furthermore, although granitization usually involves an enrichment in potash, no porphyroblastic microcline is seen in this gneiss. However, the gneiss is abnormally rich in the potash-bearing mineral biotite, and paucity of microcline may not necessarily mean paucity in potash. This might well be proved by chemical analysis.

2. The Other Metasediments.

The various mica schists and quartzites have undoubtedly been derived from the regional metamorphism of shaley and sandy facies respectively, in the original sediments.

The amphibolite, in view of its association with the epidote amphibolite and petrographic differences from the hornblende schist (which include the greater abundance of a different hornblende, the presence of a much more basic plagioclase and a rather different texture), is best regarded as differing

in mode of origin from the hornblende schists. The epidote amphibolite may have originally been an intraformational breccia or septarian nodule containing dolomitic, clayey and ferruginous material, while the associated amphibolite may have been an impure dolomite.

3. Hornblende Schist.

In view of the uniformity of composition of the hornblende schist, the fact that unlike the hornblendic lenses in the gneiss, they show no admixture of gneissic material or development of porphyroblastic felspar, and the fact that their contact with the surrounding rocks is always sharp, they appear to have been derived from the regional metamorphism of tholeiitic sills or lava flows. This hypothesis is consistent with the fact that in the first down-buckling of a geosyncline, before the most intense folding has occurred, the sediments are subject to concordant intrusions of basic magmas (Umbgrove, 1947).

4. Uralitized Quartz Dolerites.

All the later doleritic intrusions at Wattle Flat show marked uralitisation of the pyroxene and sausuritisation of the plagioclase. Rarely is any of the original pyroxene seen. The cause of this is thought to be a deuteric effect, rather than a shearing, which would cause chloritisation and not uralitisation of the pyroxene (Harker, 1932).

These dykes were apparently intruded during a period of crustal tension. Often in geosynclinal evolution a diastrophic sequence may be recognised, involving firstly orogeny, or folding, due to horizontal compression, followed by a broad uplift (epeirogeny) and finally a period of fragmentation due to tension (taphrogeny). It may be that the intrusion of these dolerite dykes was associated with this final taphrogenic period. If this were the case, the age of the dolerite would best be regarded as Archaeozoic, since the taphrogenic phase would follow fairly soon, geologically speaking, after the main orogeny which is thought to be of early Archaeozoic age. However, this is pure conjecture, and it is quite possible, although certainly not definite, that these dykes are the same age as those described by Prider (1941) from Armadale, which intrude the Cardup Series of Nullagine age. Prider (1948) considers that all of the quartz dolerites are of late-Proterozoic (post Nullagine) age.

5. Breccia.

In view of its obscure field relations the origin of this peculiar rock remains unknown. Its fragmental texture rather suggests that it may have been a fine-grained basic tuff, contemporaneous with the metasediments, but if this is the case, it is difficult to see why the hornblende has not crystallised as large, parallel orientated, subhedral prisms as it has done in the hornblende schists. Furthermore, there is no trace of directed structure. A more likely hypothesis is that the rock is part of a breccia dyke, produced by intense crushing due to the intrusion of a dolerite dyke. Apart from this crushing, the dolerite magma seems to have exerted a metasomatic effect resulting in the formation in the rock of hornblende, epidote and leucoxene. The chief objection to this theory is that no dolerite dyke was seen in the immediate vicinity, although this does not mean that one does not exist. Moreover, as the rock was found as loose boulders on the side of a hill, it has probably been transported from its place of formation.

B. THE LATER ROCKS.

1. Ferruginous Sandstone.

The occurrence of ferruginous sandstones or ferruginous grits has been described at Wongong-Cardup (Thomson, 1942), Ridge Hill (Prider, 1948), Upper Swan (Fletcher and Hobson, 1932) and Lower Chittering (Miles, 1938). At Bullsbrook ferruginous sandstones and grits, lithologically similar to the Wattle Flat rock, occur associated with leaf-bearing shales (Clarke, Prider and Teichert, 1944). It is likely that all these sandstones were formed contemporaneously.

Prider (1948) has made mechanical, heavy mineral, roundness and surface texture analyses of a specimen of ferruginous sandstone from Ridge Hill, which is similar to the ferruginous sandstone at Wattle Flat. The main points of difference between the two specimens examined are the finer grain, and consequent smaller proportion of rounded and frosted grains, and the better sorting of the Wattle Flat specimen, which also shows a greater proportion of kyanite in the heavy mineral assemblage.

Such heavy minerals as kyanite, staurolite, zircon and andalusite, that occur in the Wattle Flat ferruginous sandstone indicate that its distributive province lay in the metamorphic rocks to the east.

It is most likely that this ferruginous sandstone is part of a series of Mesozoic sediments which are found at Bullsbrook (the Bullsbrook Series) and extend north underlying marine Upper Cretaceous (at Gingin and Dandarragan) with a slight unconformity. These sediments consist of a series of breccias, conglomerates, grits, sandstones, silts, shales and clays, all of freshwater lacustrine origin. The exact age of these rocks is not known. A few poorly preserved plant remains occur in shales at Bullsbrook, and from an examination of them Walkom considered that they seemed to be more indicative of a Lower Cretaceous age than any other (Clarke, Prider and Teichert, 1944, p. 275). However, what appears to be a continuation of this series is found at Gingin, where the plant remains are of Jurassic age.

Thus it appears that the ferruginous sandstone of Wattle Flat was formed by the deposition in a lacustrine environment of the erosion products of the Precambrian rocks lying to the east. Its age is probably either Jurassic or Lower Cretaceous.

2. Laterite.

Laterites from parts of the Darling Range near Perth have been described by various authors. Simpson (1912, p. 400) writes :—" Broadly speaking, the laterite of Western Australia may be divided into two classes :—

(1) Primary Laterite (true laterite, high-level laterite), formed in situ out of soluble material derived from the weathering rock immediately underlying it.

(2) Secondary Laterite (lateritite, low-level laterite), composed largely of the mechanically transported fragments of primary laterite."

Woolnough (1918) considers that these two levels of laterite are of the same age and owe their difference in elevation to block faulting after the formation of the laterite.

Later authors in describing laterite in the Darling Range have followed Simpson in the use of terms "high and low-level laterite" to denote respectively the laterites of the higher and lower regions of the Darling Scarp.

Prider (1948) found that at Ridge Hill the laterite occurred at two distinct levels, the high-level laterite at an elevation of 700 feet above sea-level and the low-level laterite on the Ridge Hill Shelf at elevations of between 220 and 280 feet above sea-level. Furthermore, he found that whereas the high-level laterite was formed over the Pre-Cambrian complex the low-level laterite was formed over ferruginous sandstone. Both laterites, he considered, were true laterites or primary laterites formed in situ but he regarded the low-level laterite as having been formed later than the high-level laterite.

At Wattle Flat the same two varieties of laterite as described by Prider from Ridge Hill are recognised, viz., the laterite formed over the Precambrian and the laterite formed over the ferruginous sandstone. However, whereas at Ridge Hill the two types differ in elevation by about 400 feet, at Wattle Flat they are closely associated and sometimes are found at different parts of a single mesa. The occurrence of laterite at random levels and its tendency sometimes to dip towards the valleys has already been mentioned.

Fletcher and Hobson (1932) recognise two levels of laterite at Upper Swan, a high-level laterite about 700 feet above sea-level and a low-level laterite at about 200 feet to 350 feet above sea-level. They write: "The high-level duricrust is seen to grade downwards directly into granite, but at lower levels the duricrust is associated with alluvium and what might be referred to as a ferruginous sandstone. This ferruginous sandstone has also been found associated with the high-level duricrust, but in much smaller quantities." Thus it appears that, although it is not so marked, lateritized ferruginous sandstone occurs at the same level as laterite over the Pre-Cambrian, in places at Upper Swan as well as at Wattle Flat. Fletcher and Hobson regard all the laterite at Upper Swan as having been formed in situ.

From the above considerations and observations of the laterite at Wattle Flat, the following conclusions are submitted :—

(1) All the laterite at Wattle Flat has been formed in situ.

(2) In view of their close association the laterites over the ferruginous sandstone and Pre-Cambrian complex were formed contemporaneously and the differences in character between them are due entirely to the different types of rock over which they are formed.

(3) The occurrence of laterite at random levels and the presence of dipping laterite indicates that its formation did not take place on a perfectly peneplained surface and that in view of this, the significance of the terms high and low-level laterite is lost at Wattle Flat.

(4) Despite Simpson's views to the contrary, the general opinion is that laterite is a residual deposit and that its formation requires a tropical climate of alternating wet and dry seasons. Thus, it would appear that the laterite was formed at a period when the climate of Western Australia was more humid than it is now

3. The Yellow Sand Formation.

This is the youngest formation occurring at Wattle Flat and appears to be comparable to sands described by Prider (1948) at Ridge Hill and by Ivanac (unpublished Mss.) at Gillingarra.

It was seen from mechanical analysis that two types of grains occur in the yellow-sand—rounded frosted grains which tend to be concentrated in the coarser fraction and angular vitreous grains found in the finer grades. As there does not appear to be a transition from one type to the other, it is probable that they have had a different origin.

According to Twenhofel (1945), wave traction is not very effective in producing rounding in quartz grains from $\frac{1}{4}$ to $\frac{1}{2}$ mm. in diameter and cannot produce frosted surfaces on grains less than 1 mm. in diameter. If this is correct, the presence of fairly well-rounded frosted grains in considerable proportions down to a size of $\frac{1}{4}$ mm. seems to indicate that these grains at least have suffered aeolian transportation.

The heavy mineral suite found in the yellow sand is very similar to that of the ferruginous sandstone, the chief difference being the slightly greater variety of minerals in the yellow sand, which is to be expected in view of their more recent age. Their distributive province is similar to that of the ferruginous sandstone, but the latter shows finer grain, better sorting and different surface textures than are seen in the yellow sand and appear to have been formed in a different way.

The exact origin of the yellow sands cannot be stated definitely, but the indications are that they have a hybrid origin and are part aeolian. This hypothesis is supported by the presence in the yellow-sand of both rounded and euhedral zircons.

VII. SUMMARY OF THE GEOLOGICAL HISTORY OF THE AREA.

(1) In early Archaeozoic times shallow water sediments, arkoses, arkosic grits, sandstones, greywackes and shales were deposited in the basin of a subsiding geosyncline.

(2) As the downbuckling increased, a basic magma was intruded into the sediments as sills or extruded as lava flows.

(3) Then came the period of major orogeny during which the sediments and sills were intensely folded and regionally metamorphosed. This was closely followed by the granitization and associated basification of some of the sediments. An end phase of this granitization was the formation of quartz and pegmatite veins.

(4) The next period of igneous activity was the intrusion of a number of dolerite dykes, possibly either in Archaeozoic or late Proterozoic times.

(5) In Jurassic or Lower Cretaceous times occurred the deposition of the ferruginous sandstone in a lacustrine environment.

(6) Possibly in Miocene times laterite was formed over the Pre-Cambrian complex and the ferruginous sandstone.

(7) Post-dating the period of lateritization and possibly in Pleistocene times was the formation of the yellow sand.

(8) The final stage in the geological history of the area was the formation of recent deposits of alluvium and talus.

VIII. ACKNOWLEDGMENTS.

The author wishes to thank Professor R. T. Prider, Mr. A. F. Wilson, and Dr. R. W. Fairbridge for their invaluable assistance during the preparation of this paper. The co-operation of Messrs. E. W. J. Tyler and R. J. P. Lyon in the completion of the field work, and of Mr. H. J. Smith in the preparation of the photographs, has been greatly appreciated. The help of various senior students of the Department of Geology, University of Western Australia, both in the field and in the cutting of thin sections is gratefully acknowledged. Finally, the author thanks Mr. M. H. Murray of Wattle Flat for camping facilities during the field excursions. The work described in this paper was carried out with assistance from the Commonwealth Research Grant to the University of W.A. and this assistance is gratefully acknowledged.

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GEOLOGICAL MAP OF THE WATTLE FLAT AREA

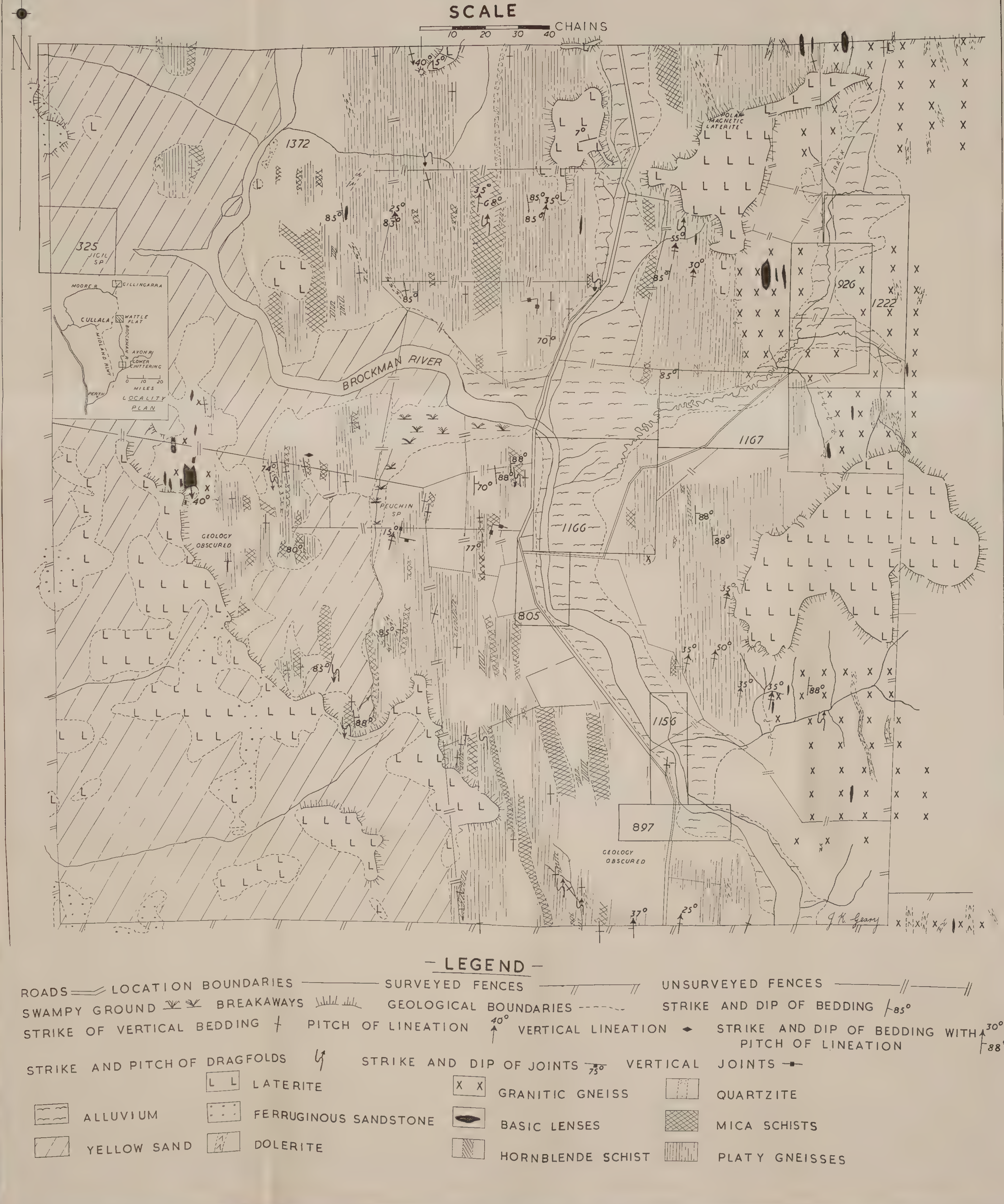

Plate II.

Fig. A.
Laterite outcropping on the banks of the Brockman River at 128N., 81W.

Fig. B.
Contact (at 50S., 50W.) between the dark-coloured residual soil over the Pre-Cambrian rocks in the foreground and background and the lighter coloured yellow sand in the middle distance. Note the difference in vegetation which is **Banksia** sp. and zamia palms (**Macrozamia**) on the yellow sand and stunted wandoo (**Eucalyptus** sp.) on the Pre-Cambrian.

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6.—SUBFOSSIL MOLLUSCS, BETWEEN ESPERANCE AND ISRAELITE BAY.

BY

Bernard. C. Cotton,
Conchologist, The South Australian Museum.

Communicated by Professor R. T. Prider ; 12th December, 1950.

Professor E. de C. Clarke has forwarded to me some interesting sub-fossils collected by him in company with Mr. Tarlton Phillipps during a trip along the south coast of Western Austrlia, between Esperance and Israelite Bay.* The shells are from salt pans and stranded beaches on the coastal plain now a few feet above sea-level.

SALT WATER LAKES.

On the " Esperance-Israelite Bay track about 33 miles east of old Thomas R. homestead on the bed of a small creek running into a salt lake " occur numerous living specimens of *Coxiella striatula* Menke, a species originally described from Rottnest Island. The genus *Coxiella* is well known as a dominant inhabitant of salt lakes in South Australia and Victoria. *C. striatula* occurs also in hard travertinised sand in the " Esperance-Israelite Bay track about three miles back towards Esperance before reaching Port Malcolm, on a clay pan forming low cliffs three feet in height on the side of the lake." Another species of *Coxiella* similar to the South Australian *C. confusa* Smith, is also in great quantities in a " Recent swamp deposit, Duke of Orleans Bay, at the crossing of Duke Creek " and some specimens are embedded in partly travertinised sand. This species is found abundantly in the Coorong of South Australia alive and sometimes in travertinised sand in the same area.

FINE SAND BEACH.

This name is used to describe the type of beach which is found in protected waters and semi-estuarine conditions, where the sand is fine and not coarse as it is frequently found on open ocean beaches. The littoral fauna is very consistent right along the southern Australian coast, the species showing sub-specific rather than specific differences at the extreme east and west. Subfossil living species are represented at the different sites. Large specimens of the sand cockle, *Katelysia scalarina* were found beside the " Esperance-Israelite Bay track between Port Malcolm and Israelite Bay about four miles from Ponton's old homestead—on side of salt lake." They are abundant and form shell banks appararently similar to those of the South-East of South Australia, mentioned by Crocker and Cotton 1946, Trans. Roy. Soc. S. Aust., 70, (2), p. 67, fig 3. The following species were also found in this locality :—Marine Pelecypoda : *Anadara trapezia*, *Ostrea sinuata* and large specimens of *Cardium racketti*. Marine Gastropoda : *Niotha pyrrhus*, large *Parcanassa pauperata* which prey on *Katelysia scalarina*, *Uber conicum* the Sand Snail, and *Akera bicincta*, also *Cominella eburnea* and *C. lineolata* both of which live on pebble reefs sometimes found in otherwise sandy areas.

* I wish to apologise to Mr. Cotton, who sent me these notes in March, 1948, for my delay in submitting them to the Royal Society of Western Australia.

E. de C. C.

CONCLUSION.

The salt-lake shells *Coxiella striatula* and *Coxiella* cf. *confusa* occur in great quantities alive and as subfossils in the travertinised sand-banks. This formation is comparatively recent and subsequent to the Mid-Recent Epoch.

The stranded beaches have a fine-sand to estuarine suite of shells remarkable in that they are frequently comparatively large, suggesting that conditions, ecological, climatic and geographic, were more congenial than those under which the same species live today. This stranded beach deposit is almost certainly contemporary with the well known 15 ft. to 20 ft. eustatic beach developed around the coast of Southern Australia. It has recently been found behind the Woakwine Range of south-east South Australia where R. C. Sprigg and myself discovered the first authentic specimens of *Anadara trapezia* in this area. Although the Woakwine Range may have been originally formed during the Late Pleistocene about 100,000 years ago, the deposit here being considered is of a more recent age, and formed when a shallow arm of the sea flowed behind the Woakwine and gave the warm shallow water *Zostera* flat conditions to support *Anadara trapezia*. During the Mid-Recent 15 ft. to 20 ft. emergence estimated to have occurred about 4,000 years ago, the onset of lower temperatures quickly wiped out the exposed surface dwelling *Anadara trapezia* while the accompanying wetter and cooler conditions were favourable to the growth of larger fine-sand and estuarine species such as those listed above.

OBITUARY

THE LATE MR. ANDREW GIBB MAITLAND (1864-1951).

Statement by President of the Royal Society, Mr. G. H. Burvill, to General Meeting of the Society, Tuesday, 13th March, 1951.

Since our last meeting death has claimed a very old and honoured member of this Society. I refer to the late Mr. Andrew Gibb Maitland, formerly Government Geologist in Western Australia. Mr. Gibb Maitland was well known and will be long remembered for his scientific work in this State in the field of geology, and I will refer later to a few aspects of his work. It is fitting, however, that at a meeting of this Society I should remind you that the Society owes its foundation directly to the late Mr. Gibb Maitland. Mr. Gibb Maitland was an original member of the Mueller Botanic Society in this State. That Society was succeeded by the Natural History and Science Society and this in turn by the Royal Society of Western Australia. The late Mr. Gibb Maitland moved the resolution which ultimately led in 1913 to the formation of the Royal Society. He was for very many years a member of the Council of this Society and was twice President. He also acted for over a quarter of a century as the local Honorary Secretary of the Australian and New Zealand Association for the Advancement of Science.

Mr. Gibb Maitland was born in England on the 30th November, 1864 and was in his 87th year at the time of his death (28th January, 1951). His education at Victoria College, Leeds, embraced geology, mining engineering and surveying under a number of distinguished geologists and engineers. He joined the Geological Survey of Queensland in 1888 and did notable geological work in New Guinea in 1891. He came to Western Australia as Government Geologist in 1896 when the gold discoveries had caused a tremendous boom in Western Australia. He continued in that position for 30 years. Two very notable personal contributions to the geology of Western Australia will serve to remind us of the importance of Mr. Gibb Maitland's work. Soon after he came to Western Australia his attention was concentrated on the matter of water supply. After studying the country along the coast for nearly 300 miles south of North-West Cape, he concluded that artesian water should be available there and his prediction proved correct. Many sheep stations in these areas are now served with water supplied by artesian bores. Later he predicted that artesian water would be found in the country near Derby, and in the Nullarbor Plains, and both these predictions were fulfilled.

In the 1903-1906 period Mr. Gibb Maitland carried out a geological survey of the Pilbara Goldfield under most arduous conditions. In this work he discovered the order of succession of the very old and intensely altered rocks of the region, and this work has served as a key in the interpretation of the similar, but often more obscure, rocks of the chief goldfields of the State and their ore deposits.

Throughout his 30 years service as Government Geologist, Mr. Gibb Maitland directed the work of the Geological Survey towards a knowledge of the geological structure of the whole State in general, while at the same

time providing detailed and special information, particularly in relation to mining. Before he retired a geological map of the whole of the State—an area of almost one million square miles—was produced, and it had very few blank spaces.

Mr. Gibb Maitland's work for science was recognized by the award to him of the Von Mueller Medal by the Australian and New Zealand Association for the Advancement of Science, also the Clark Memorial Medal of the Royal Society of New South Wales. In 1937 the Kelvin Medal of the Royal Society of Western Australia was awarded to him.

Mr. Gibb Maitland's interest in the Royal Society continued after his retirement right up to his death. In past years he donated to the Society various journals and books from his extensive library. In his will he bequeathed to the Society "his scientific books or such of them as the Society might care to choose." This offer has resulted in the recent addition of a number of valuable journals and books to the Society's library.

The late Mr. Gibb Maitland's work for, and interest in, science in Western Australia, extending for more than half a century, will stand as an inspiring example for the future.

SOME OPTICAL PROPERTIES OF CONCAVE MIRRORS AND THEIR APPLICATION TO THE X-RAY MICROSCOPE.

PRESIDENTIAL ADDRESS, 1950.

By
J. SHEARER, B.A., M.Sc., F.Inst.P.

Delivered 11th July, 1950.

I. OPTICAL PROPERTIES.

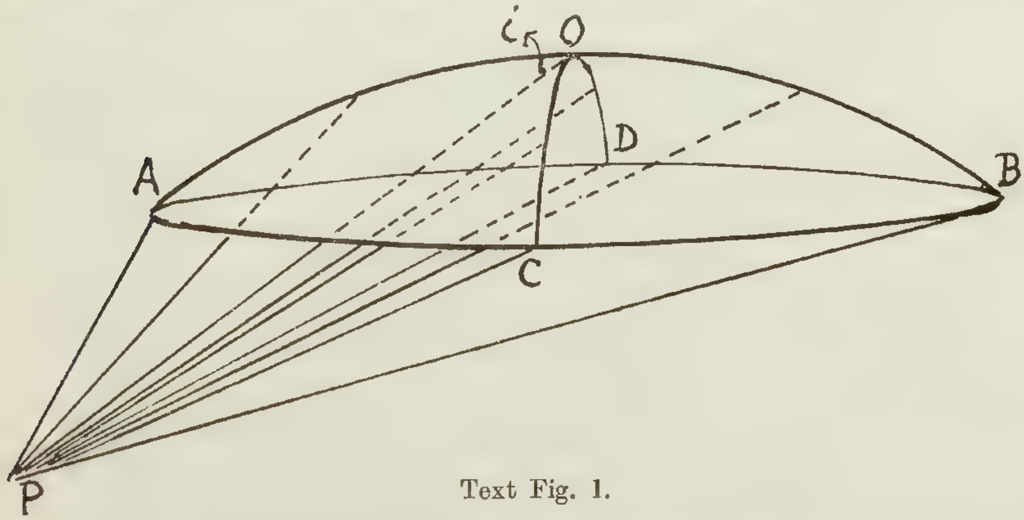
The positions of point object and corresponding image, in the case of a concave spherical mirror with object (and therefore image) on the axis, are given by the relation

$$1/f = 1/p + 1/q.$$

Here p is the distance of the object from the pole of the mirror, q the image distance, and f a constant, the focal length. The focal length is equal to $R/2$ where R is the radius of curvature of the mirror. If we designate the principal focus by F, then provided the object is situated somewhere between F and infinity a real image is formed somewhere between infinity and F.

The formula holds provided the aperture of the mirror is small. More precisely, the formula is true for all real images provided the ratio of the semi-aperture to the focal length is small.

The geometrical optics of a concave spherical mirror when the object is not situated on the axis of the mirror are not so widely known. In this case two groups of rays may be distinguished. For one group, called the meridian rays, the plane of curvature of the section from which reflection takes place (the meridian plane) coincides with the plane of incidence of all



Text Fig. 1.

the rays. For the other group, called the sagittal rays, the plane of curvature of the section from which reflection takes place (the sagittal plane) is perpendicular to the plane of incidence of any one of the rays. In text figure 1 showing incident rays only, the meridian rays are incident along the arc AOB and the sagittal rays along the arc COD. PO, whose grazing angle of incidence is i, is common to both groups.

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It may be shown (1) that for meridian rays the focal length (meridian focal length) is

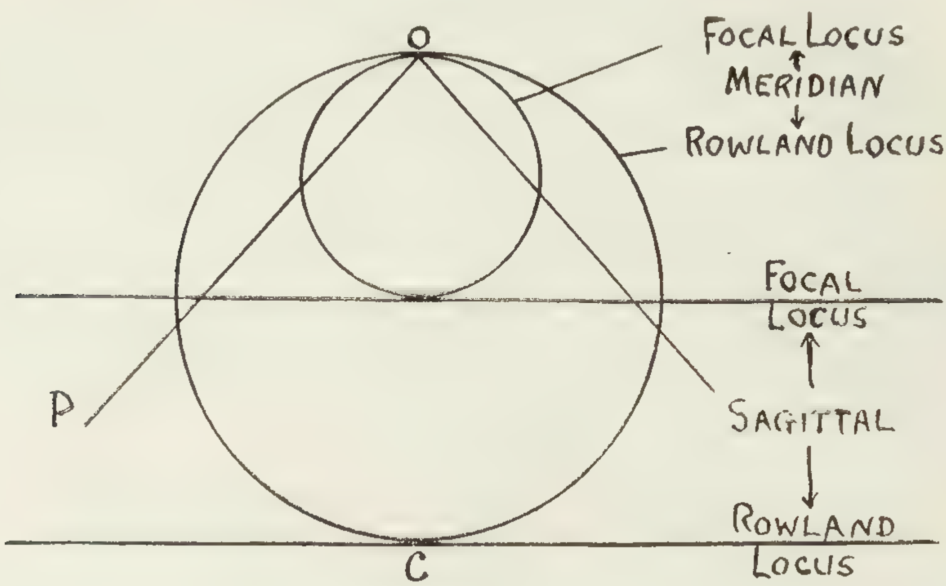
$$f_m = (R \sin i)/2$$

and that for sagittal rays the sagittal focal length is

$$f_s = R/(2 \sin i).$$

These both assume the value $R/2$ for an object on or near the axis.

In text figure 2 a general picture may be obtained of the geometrical optics of a small concave spherical mirror situated at O and with centre of curvature at C. The Rowland locus is the locus of image (and object) when the magnification is unity. For any incident pencil PO there will be two



Text Fig. 2.

focal lengths and no true image will be formed. Where an image is formed by the meridian rays astigmatism parallel to the sagittal plane will occur. Where an image is formed by the sagittal rays astigmatism parallel to the meridian plane will occur. The object-image relationship for a concave spherical mirror is expressed by the two equations :

$$1/p + 1/q_m = 1/f_m = 2/(R \sin i)$$
$$1/p + 1/q_s = 1/f_s = (2 \sin i)/R.$$

These hold provided the aperture is small. If i is also small the meridian aperture must be vanishingly small for the first equation to hold. The sagittal aperture is not so restricted.

To produce an image free from astigmatism two " crossed " mirrors may be used. Two mirrors are said to be " crossed " when meridian rays from the first are incident on the second as sagittal rays, and vice versa. The theory of such a combination is developed in the reference given (1). If the meridian focal lengths of the two mirrors are equal ($f_m = f'_m$), and if the sagittal focal lengths are also equal ($f_s = f'_s$), there is only one separation (zero) that will give a single final image. The same will approximately apply if the minimum separation possible with two mirrors (the sum of their semi-apertures) is small compared with the object distance and the image distance.

The formula for such a combination of spherical mirrors, when $f_m=f'_m$ and $f_s=f'_s$, is

$$1/F=1/f_m+1/f_s=1/p+1/q.$$

If the two "crossed" mirrors are cylindrical (with $f_s=f'_s=\infty$) the formula becomes

$$1/F=1/f_m=1/p+1/q.$$

The same result may be achieved with two "parallel" cylindrical mirrors when $f_s=f'_m=\infty$ and $f_m=f'_s$. (In the case of "parallel" mirrors meridian rays reflected from the first mirror constitute meridian rays incident on the second mirror).

When i is small (object very remote from the axis) spherical mirrors behave approximately as cylindrical mirrors since $R/(2 \sin i)$ in this case is very large.

It is difficult to ensure experimentally that in the case of "crossed" cylindrical or spherical mirrors $f_m=f'_m$ and $f_s=f'_s$ or that in the case of "parallel" cylindrical mirrors $f_m=f'_s$. This condition is more easily ensured if a single surface can be prepared with meridian and sagittal radii of curvature (R_m and R_s) so related that $f_m=f_s$. The required relation is obviously

$$R_s/R_m=\sin^2 i.$$

The adjustment then required to ensure equality of f_m and f_s is the single adjustment for the correct incidence i. One advantage of such a mirror is that an achromatic unastigmatic image may be produced, and the beam simultaneously deflected through a given angle, by one and the same optical system. If the mirror is designed for grazing incidence i the beam is deviated through $2i$.

II. APPLICATION TO THE X-RAY MICROSCOPE.

It has long been known that X-rays have an observable refractive index slightly less than unity. If the refractive index be written $1-\delta$, for X-rays of wave-length of the order of $1 Å$ δ is of the order of 10^{-5}. Specular reflection, in the nature of total external reflection, is therefore observed when such radiation is incident upon surfaces at sufficiently small grazing angles.

Only recently have serious attempts been made to make use of such specular reflection in the formation of X-ray images by concave reflectors. Ehrenberg (2) obtained converging beams by total reflection from plates bent under constraints to form an approximately parabolic surface. The convergence was accompanied by weak "scattered" radiation most of which was traceable to imperfections of the optical flats.

An extensive theoretical and experimental study of the problem of producing images by X-rays incident on concave mirrors at small grazing angles has been made by Kirkpatrick and Baez (3). The unusual conditions can be appreciated when it is realised that the critical grazing angle of incidence for total reflection is theoretically much less than one degree except for very long wave-lengths. The meridian and sagittal focal lengths therefore become $Ri/2$ and $R/2i$ respectively for a spherical mirror. The ratio of these is

greater than 10^4 and a concave mirror behaves appreciably as a cylindrical mirror with R_s infinite. Provided the aperture is sufficiently small for the angle α subtended at the centre of curvature by the semi-linear aperture of the mirror to be equal approximately to its sine, the formula for the meridian rays becomes

$$\frac{1}{q + 2af_m} + \frac{1}{p - 2af_m} \cdot \frac{2 - a}{2 + a} = \frac{1}{f_m(1 + a/2)}$$

where $a = \alpha/i$. When $\alpha \ll i$ the formula simplifies to

$$1/q_o + 1/p = 1/f_m.$$

Kirkpatrick and Baez then examine the spherical aberration measured as $q - q_o$. If *all* terms in a^2 are neglected we get

$$q - q_o = q_o a \frac{3M - 3}{2 - 3aM}$$

corresponding to their equation (5). Here M is the magnification given by q_o/p. If a is small and M not too large the aM term is small and increases with a, causing the " wandering of the focus " $(q - q_o)$ also to increase. At higher magnifications the increase in $q - q_o$ will be more rapid. Therefore, with a given α, i should be as large as possible.

In the same article by Kirkpatrick and Baez the authors adopt, as a measure of " image impairment," $(q - q_o)\,\delta$ where 2δ is the angle subtended by the mirror at the image. Using the above equation for $(q - q_o)$ we finally get

$$(q - q_o)\delta = S = \tfrac{3}{2}R\alpha^2\,(M - 1)$$

which becomes, for $M \gg 1$, $S = \frac{3}{2}R\alpha^2 M$. Now S/M is an object dimension corresponding to an image dimension S and is therefore a measure of the resolution permitted by spherical aberration when the magnification is large. To resolve features separated by about $6000A$ a mirror of 10 metres radius would require to have an aperture of 4 mm.

The authors then examine resolving power, on the basis of the wave-theory, for a mirror assumed free from geometrical aberrations. Two other important assumptions are made. The first is that the maximum aperture to give total reflection is used. The maximum angle ϕ in the meridian plane that the mirror can subtend at the object is limited by the maximum value i can have (that is, by the critical grazing angle for reflection i_c). ϕ is shown to be $2i_c$ for an elliptic or parabolic mirror. The other assumption is that two object points are resolved when the diffraction maxima are separated by a distance at least equal to that between either maximum and its adjacent minimum. It then follows that the minimum separation of resolvable objects, or the resolution, is $\lambda/2i_c$. Now i_c is equal to $\lambda(ne^2/\pi mc^2)^{\frac{1}{2}}$. Here e (e.s.u.), m and c have their usual significance and n is the number of electrons per cm^3. This gives for the resolving power $\frac{1}{2}(\pi mc^2/ne^2)^{\frac{1}{2}}$. A striking feature of this expression is its independence of λ. For platinum (for which n is large) this expression is about $70A$. This is a highly ideal figure, particularly for the reason that for an aperture smaller than that assumed here spherical aberration has been shown to limit the resolution to $6000A$ in the case of a spherical mirror.

To obtain 2-dimensional images " crossed " mirrors must be used. In the publication cited Kirkpatrick and Baez reproduce an image of a 350 mesh gauze showing an X-ray magnification of 29 diameters. The radius of the spherical mirror was 21.9 metres, and the wave-length of the order of $1A$. A more recent announcement (4) reports that, with " crossed " elliptical glass mirrors (metal-coated and uncoated) and radiation of about $2.3A$ wave-length single-stage magnifications up to 100 diameters have been obtained. To avoid air absorption the microscope is filled with helium at one atmosphere. The resolution obtained with such X-ray images permits of higher magnifications being obtained by enlargement. Special emulsions have been prepared (particularly for electron microscopy) that permit of enlargement up to several hundred diameters. This would give more total magnification, however, than an X-ray microscope as at present designed would usefully permit. Even taking a resolution of $100A$ and assuming the resolution of the eye to be 10^{-2} cm., the maximum useful magnification is 10,000.

Larger grazing angles of incidence are highly desirable particularly in order to reduce geometrical aberration. To achieve this, advantage can be taken of the fact that the theoretical critical grazing angle for reflection increases proportionately with increase in λ. Moreover the reflection is not in practice highly critical and occurs with reduced intensity for grazing angles larger than the critical. Faint reflection of carbon radiation (predominantly $K\alpha$ radiation of $45A$) from quartz and glass has been reported (5 and 6) up to 40° and 45° respectively. Farrant (7) has suggested a method of mounting organic substances for X-ray microscopy using long (and therefore highly absorbable) wave-lengths.

With considerably larger grazing angles than have been used to date in developing an X-ray microscope the prospects are more favourable of being able to use a single toroidal mirror conforming to the relation

$$R_s/R_m = \sin^2 i.$$

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